Instituto Federal de Educação, Ciência e Tecnologia de Santa Catarina
Departamento Acadêmico de Eletrônica
Pós-Graduação em Desen. de Produtos Eletrônicos
Conversores Estáticos e Fontes Chaveadas

# Modelagem e Controle de Conversores

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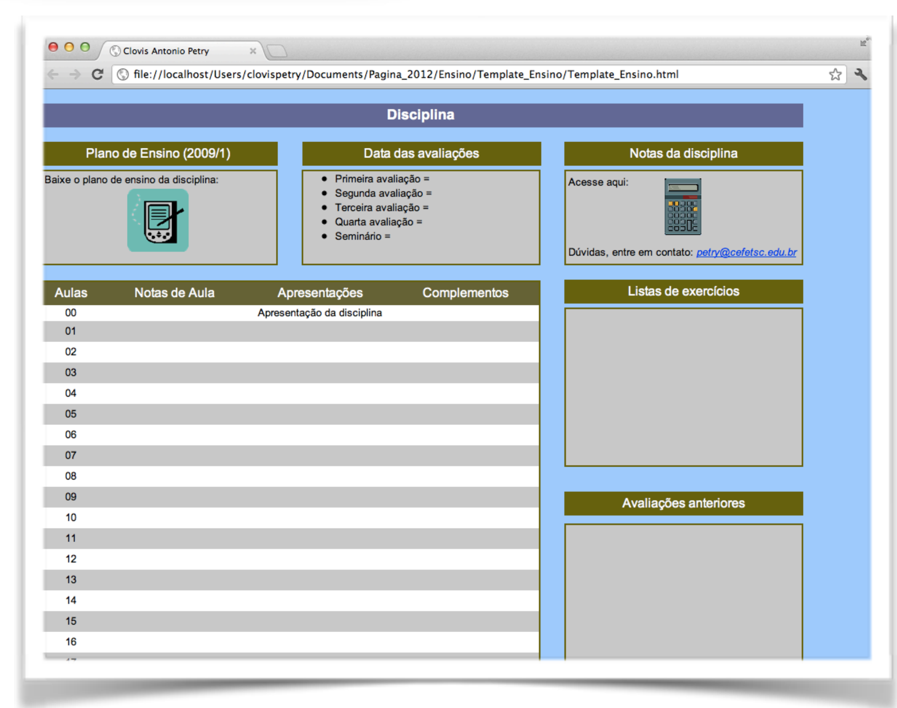
Prof. Joabel Moia.

Florianópolis, maio de 2014.

# Biografia para Esta Aula

**Modelagem e controle de conversores:**

- Conversores operando em malha fechada;
- Comportamento de componentes passivos;
- Diagramas de bode;
- Função de transferência de conversores;
- Simulação em malha aberta (planta x modelo);
- Função de transferência do estágio de modulação.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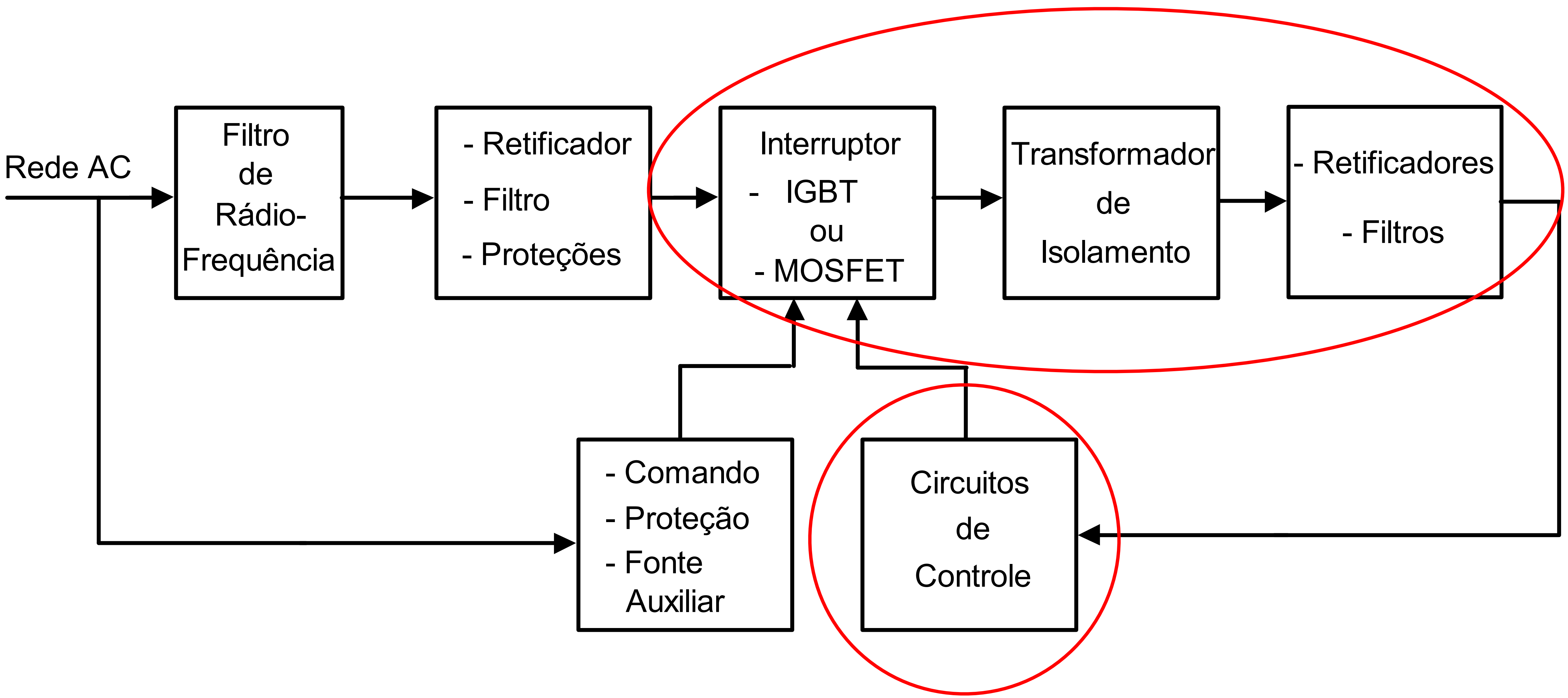
# Nesta Aula

**Modelagem e controle de conversores:**

- Conversores operando em malha fechada;
- Comportamento de componentes passivos;
- Diagramas de bode;
- Função de transferência de conversores;
- Simulação em malha aberta (planta x modelo);
- Função de transferência do estágio de modulação.

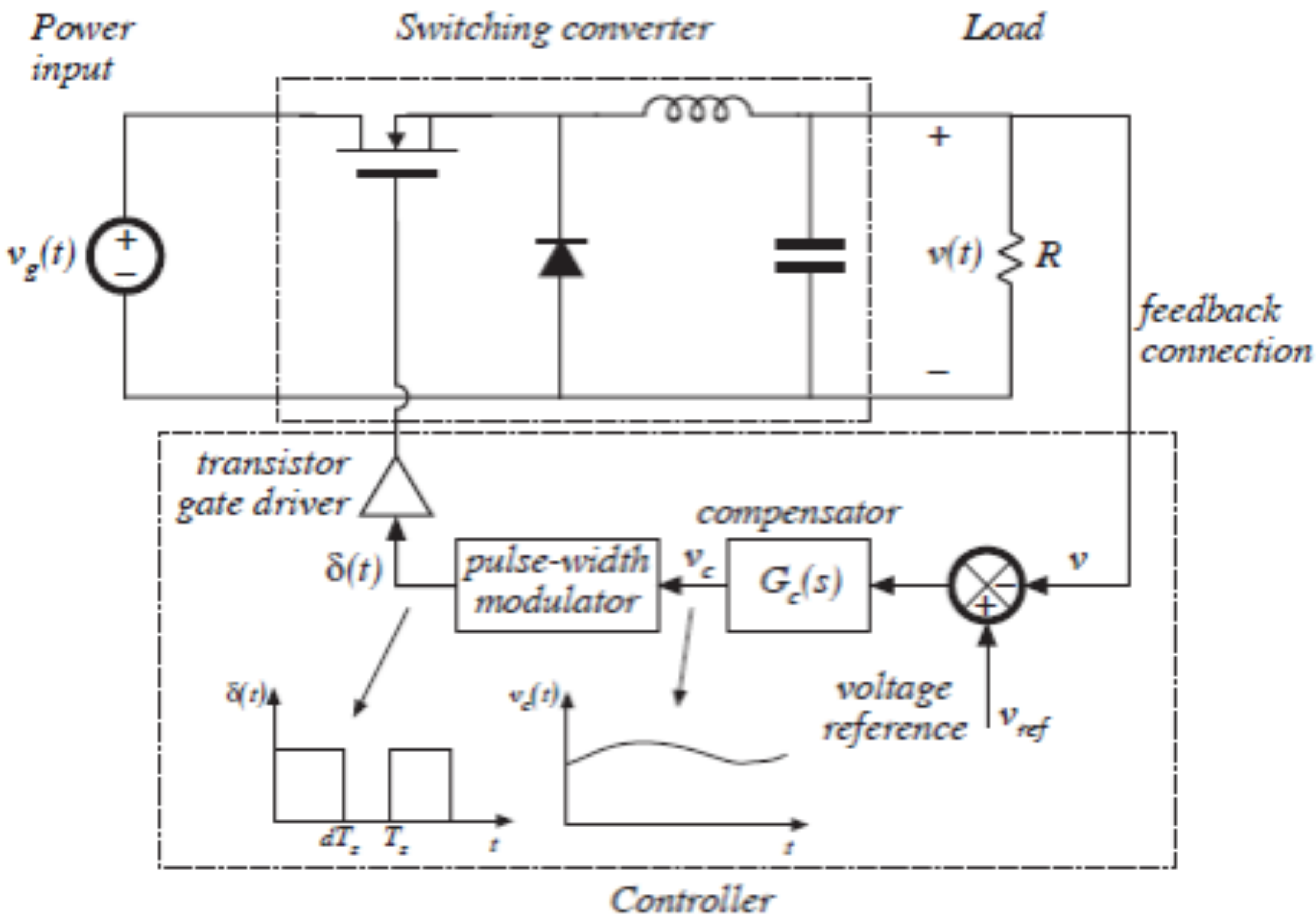
# Modelagem e Controle de Conversores

Diagrama de blocos de uma fonte chaveada:



# Modelagem e Controle de Conversores

## Conversor Buck

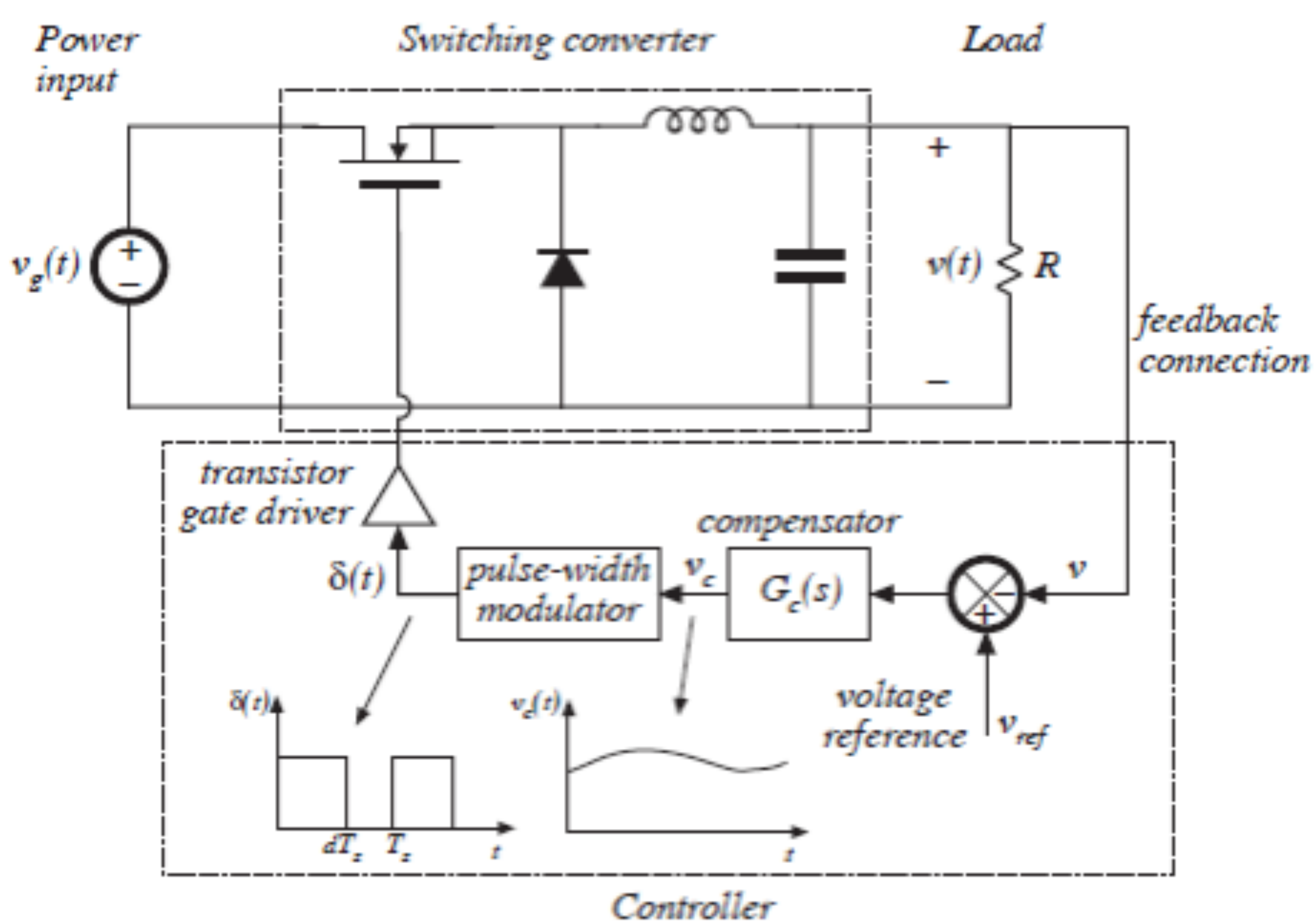


# Modelagem e Controle de Conversores

**Objetivos das malhas de controle:**

• Garantir a precisão no ajuste da variável de saída;

• Rápida correção de eventuais desvios provenientes de transitórios na alimentação ou mudanças na carga.

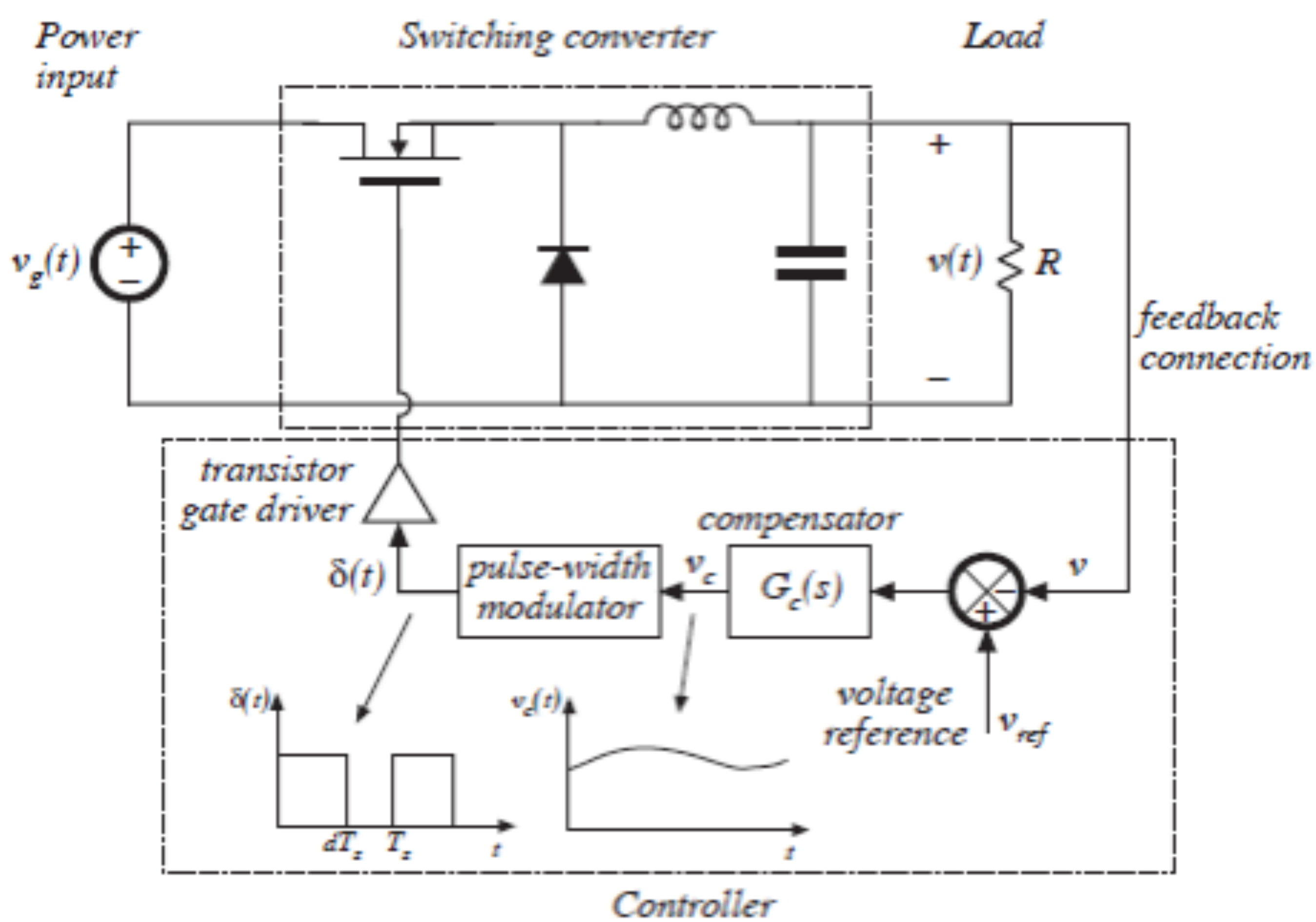


# Modelagem e Controle de Conversores

**Modelagem:**

- Busca a relação entre a tensão de saída e a tensão de controle.

- Tensão de controle é fornecida pelo compensador, a partir do erro existente entre a referência e a tensão de saída.

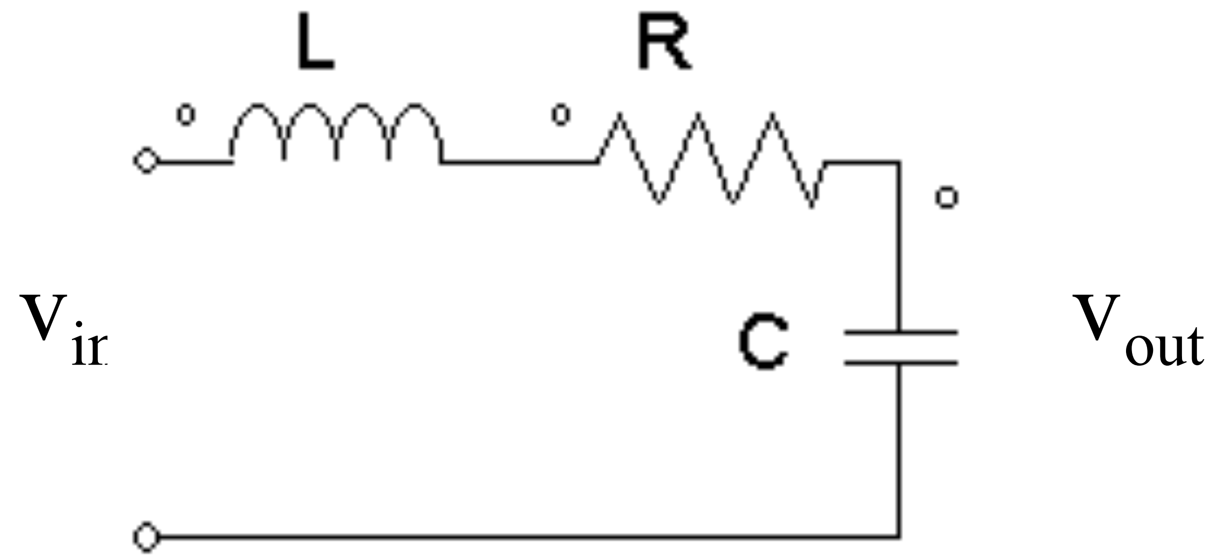


# Comportamento dos Componentes Passivos

| | Domínio do tempo | Domínio da freqüência |
|---|---|---|
| **Resistor** | $v_R = R \cdot i$ | $V_R(s) = R \cdot I(s)$ |
| **Indutor** | $v_L = L \cdot \dfrac{di}{dt}$ | $V_L(s) = s \cdot L \cdot I(s)$ |
| **Capacitor** | $v_C = \dfrac{1}{C} \cdot \int i \cdot dt$ | $V_C(s) = \dfrac{1}{s \cdot C} \cdot I(s)$ |

# Comportamento dos Componentes Passivos

Circuito RLC série




Domínio do tempo

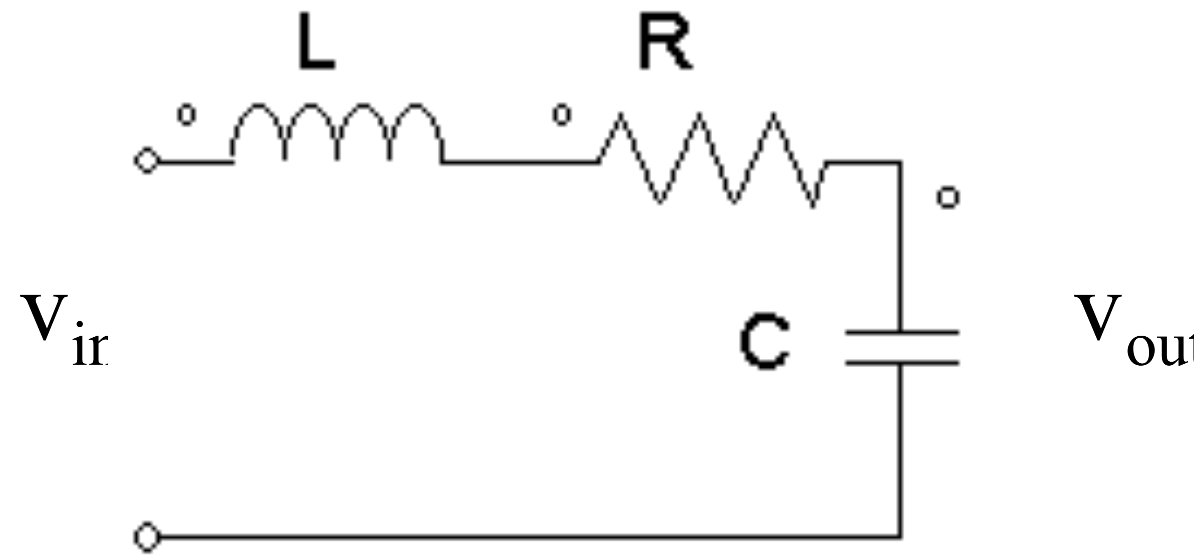
Domínio da freqüência

$$v_{in} = L\frac{di}{dt} + R \cdot i + \frac{1}{C}\int i \cdot dt \qquad V_{in}(s) = L \cdot s \cdot I(s) + R \cdot I(s) + \frac{1}{s \cdot C} \cdot I(s)$$

$$v_{out} = \frac{1}{C} \cdot \int i \cdot dt \qquad V_{out}(s) = \frac{1}{s \cdot C} \cdot I(s)$$

# Comportamento dos Componentes Passivos

## Circuito RLC série




$$V_{out}(s) = \frac{1}{s \cdot C} \cdot I(s)$$

$$V_{in}(s) = L \cdot s \cdot I(s) + R \cdot I(s) + \frac{1}{s \cdot C} \cdot I(s)$$

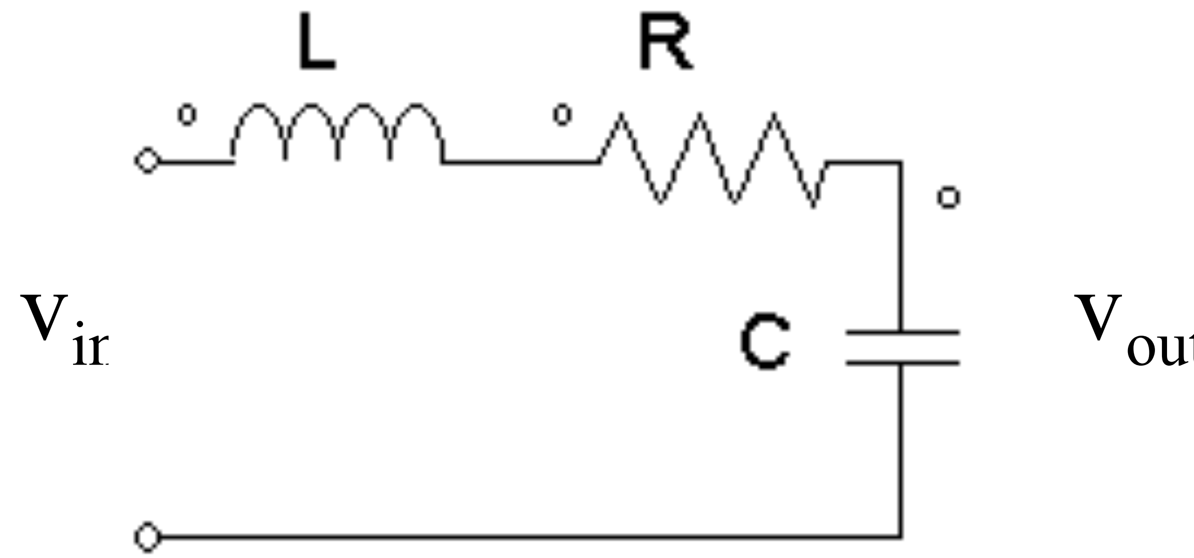
## Função de transferência

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{\frac{1}{s \cdot C} \cdot I(s)}{L \cdot s \cdot I(s) + R \cdot I(s) + \frac{1}{s \cdot C} \cdot I(s)}$$

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{L \cdot C \cdot s^2 + R \cdot C \cdot s + 1}$$

# Comportamento dos Componentes Passivos

Circuito RLC série




$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{L \cdot C \cdot s^2 + R \cdot C \cdot s + 1}$$

$$s = j\omega$$

Corrente contínua $\quad s \rightarrow 0$

Alta freqüência $\quad s \rightarrow \infty$

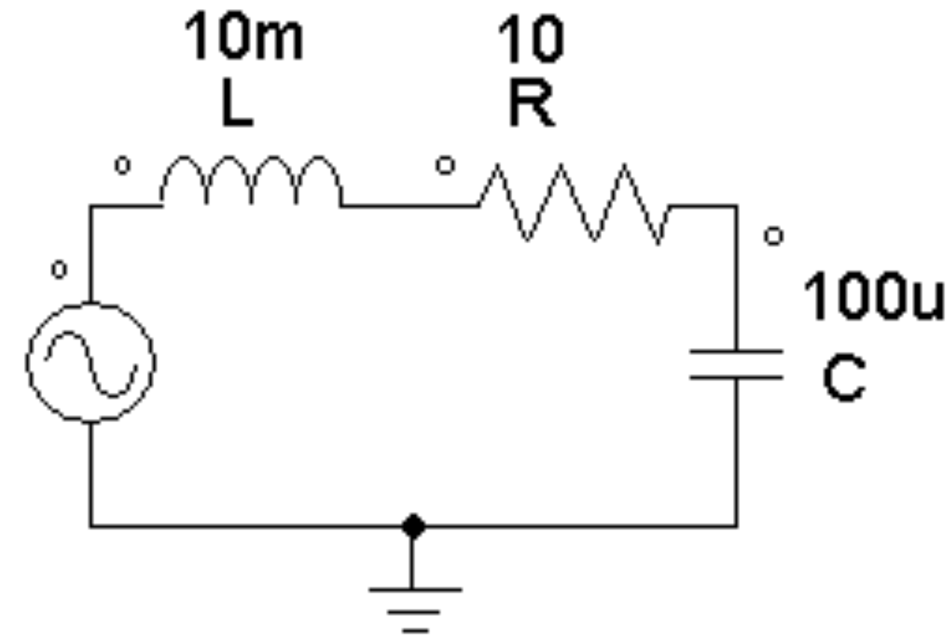
$$\frac{V_{out}}{V_{in}} = \frac{1}{L \cdot C \cdot 0^2 + R \cdot C \cdot 0 + 1} = 1$$

$$\frac{V_{out}}{V_{in}} = \frac{1}{L \cdot C \cdot \infty^2 + R \cdot C \cdot \infty + 1} = 0$$

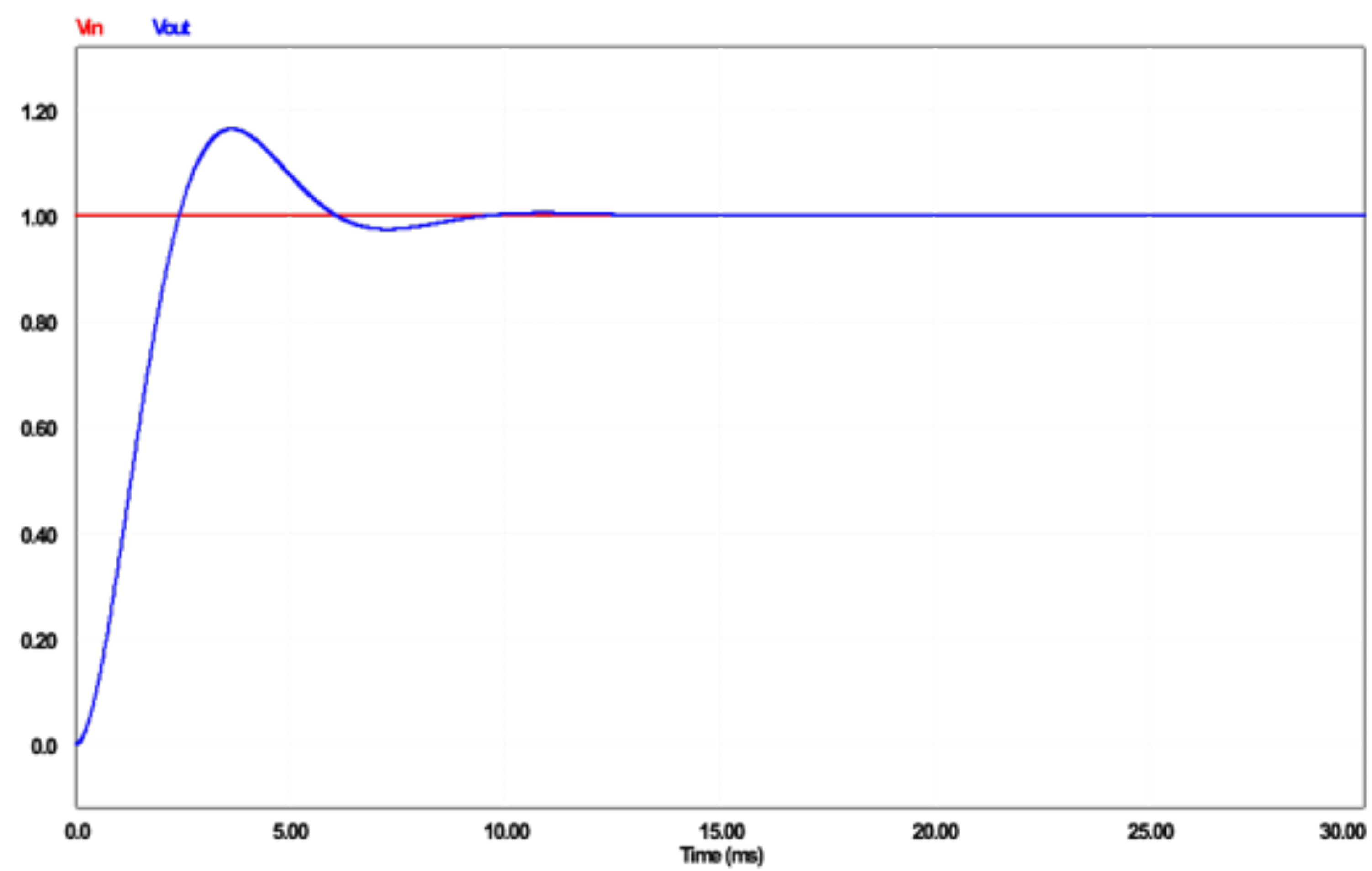
# Comportamento dos Componentes Passivos

## Circuito RLC série

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{L \cdot C \cdot s^2 + R \cdot C \cdot s + 1}$$



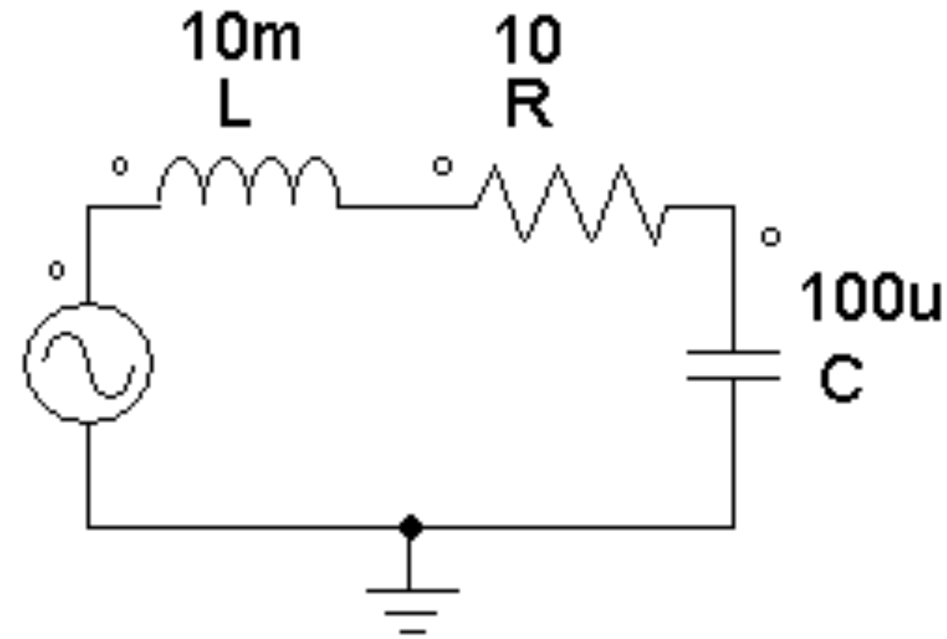

## Corrente contínua



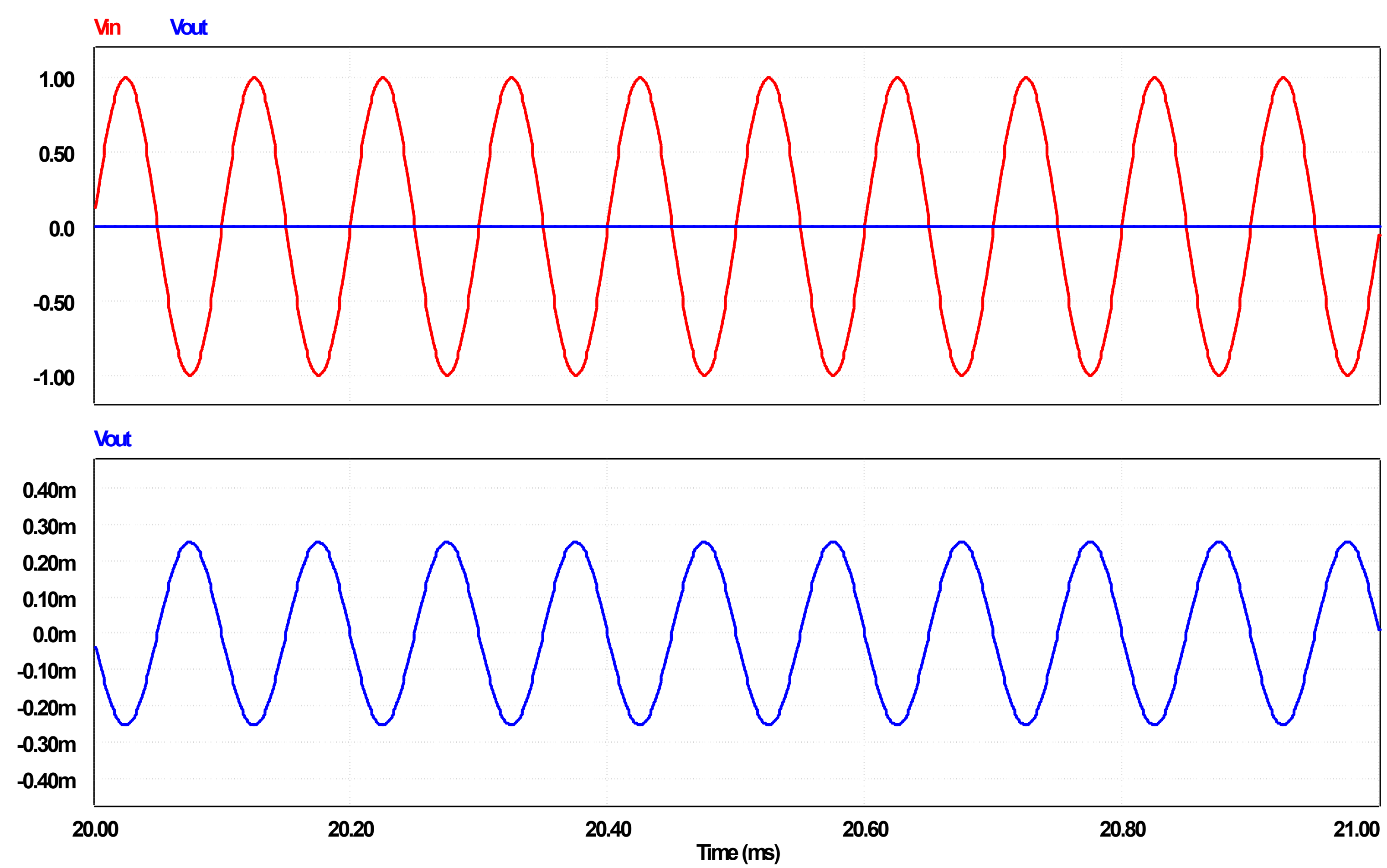
# Comportamento dos Componentes Passivos

Circuito RLC série

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{L \cdot C \cdot s^2 + R \cdot C \cdot s + 1}$$



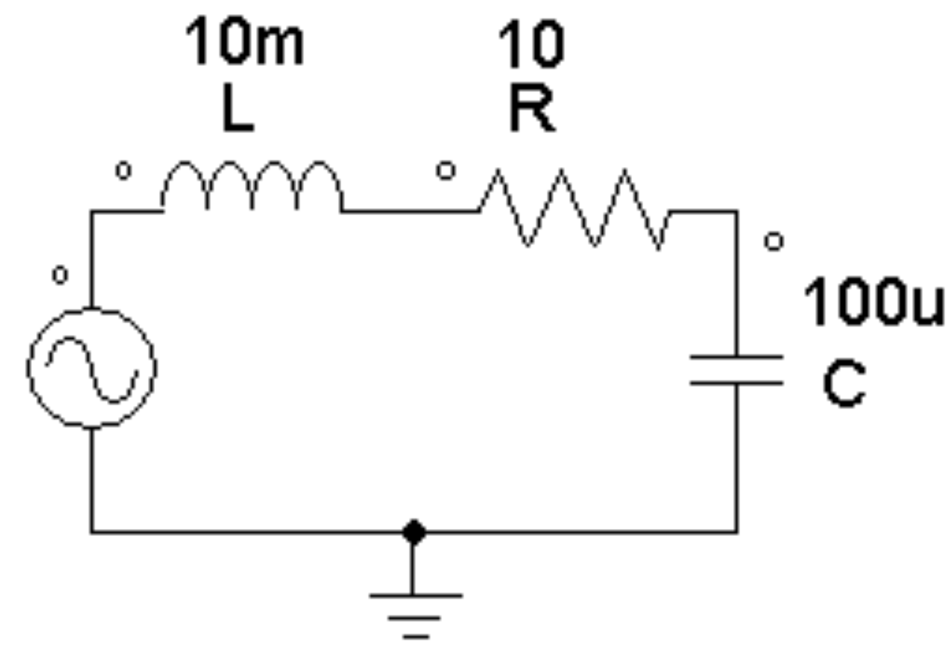

Alta freqüência
10kHz



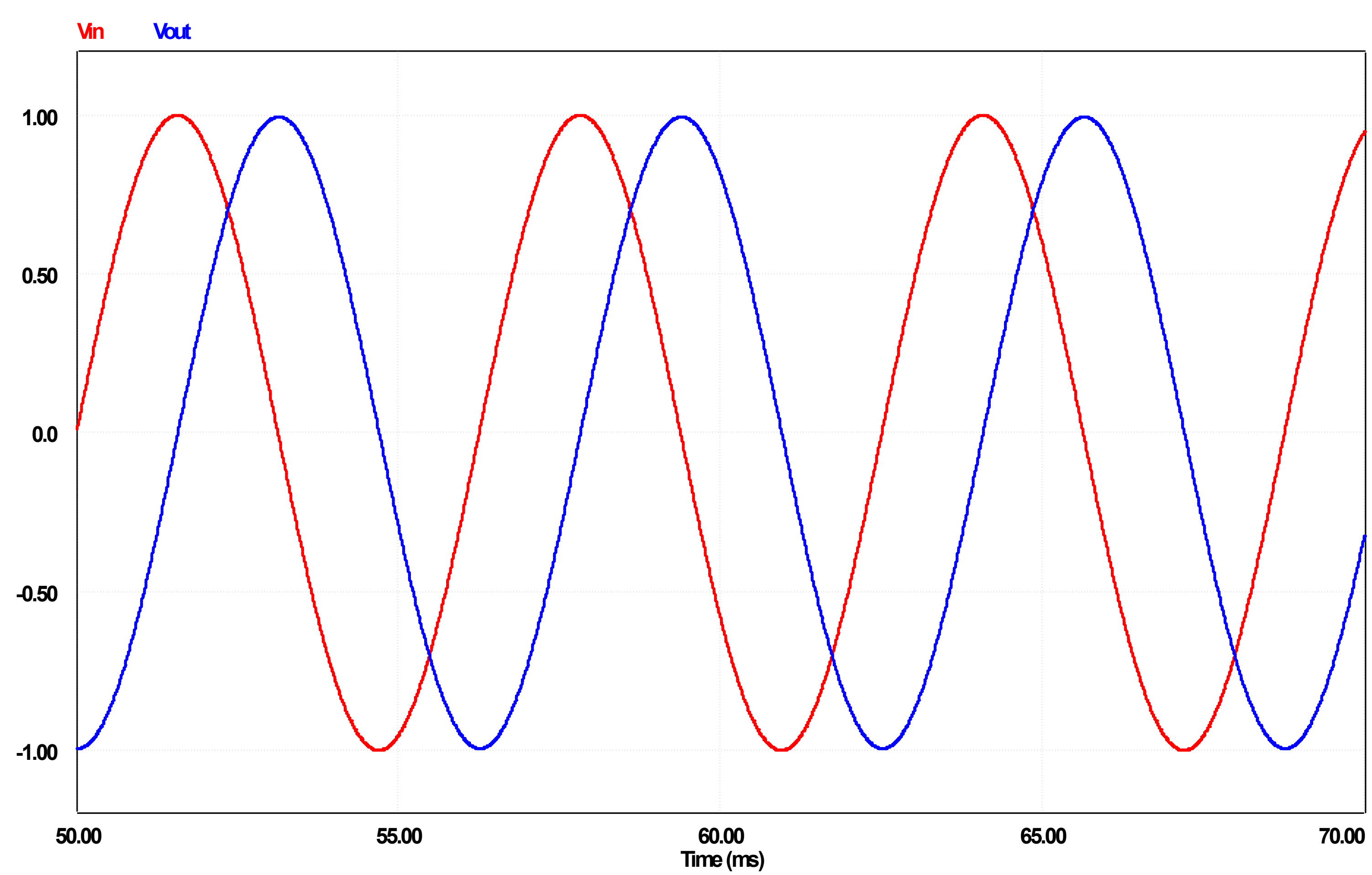
# Comportamento dos Componentes Passivos

Circuito RLC série

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{L \cdot C \cdot s^2 + R \cdot C \cdot s + 1}$$



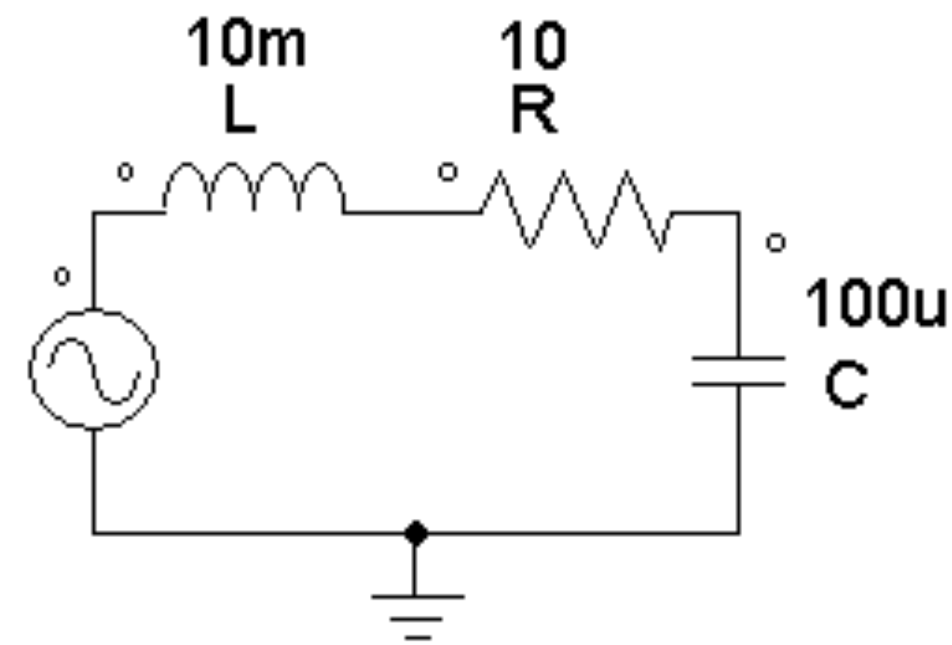

Média freqüência
160Hz

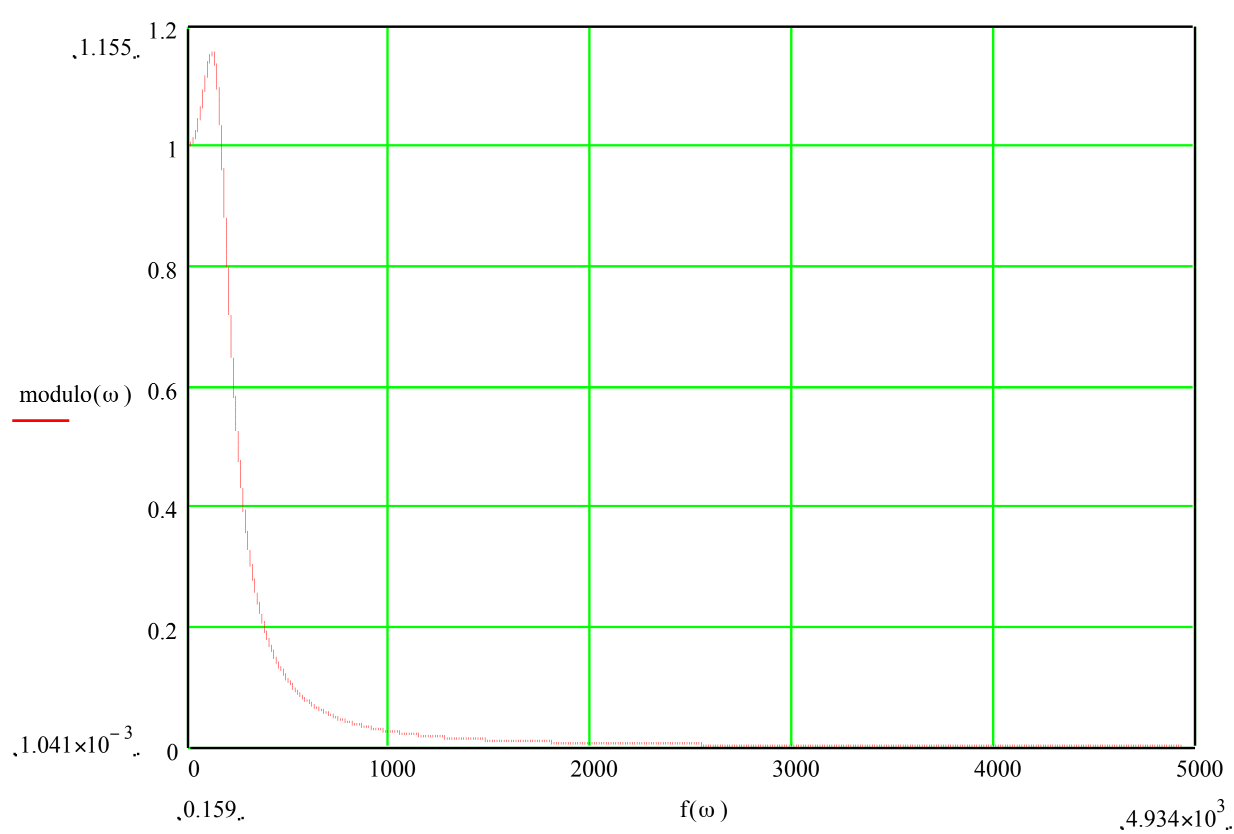


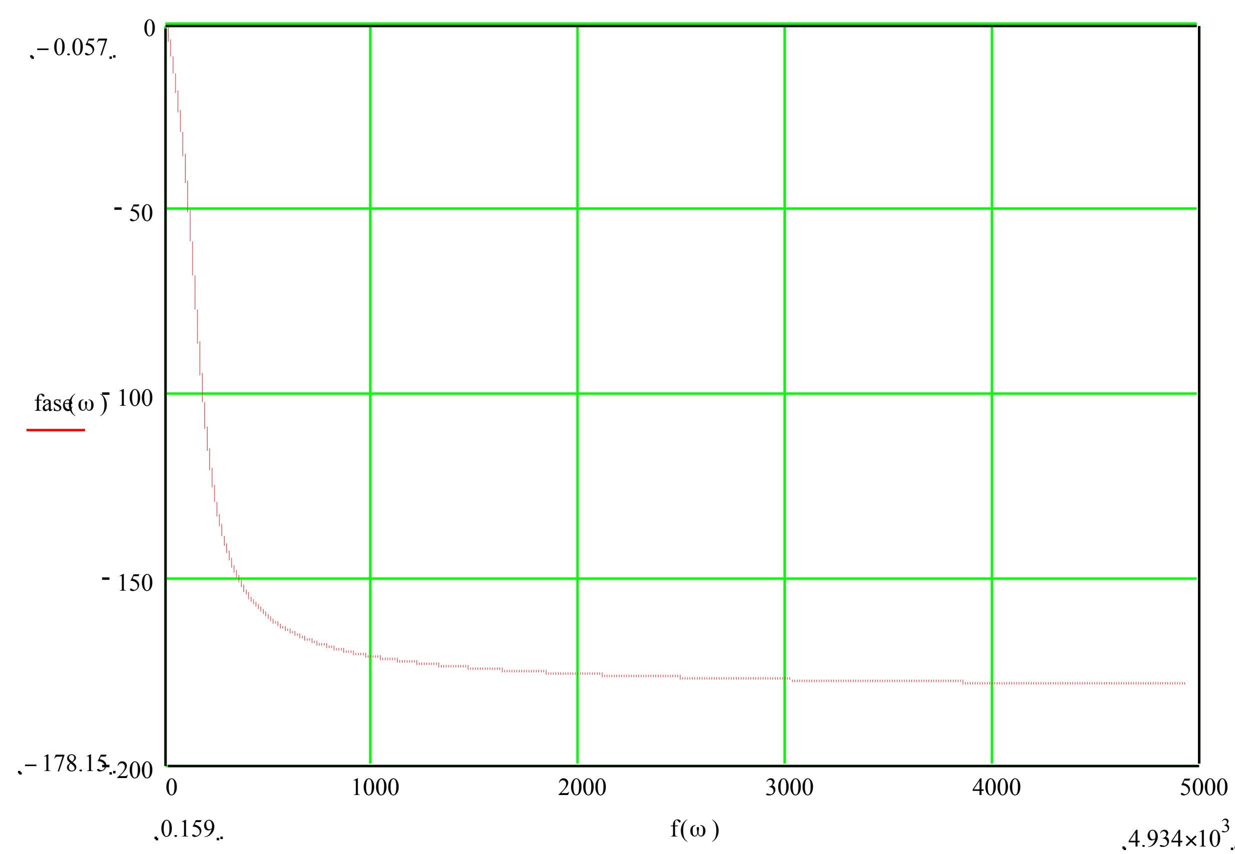
# Comportamento dos Componentes Passivos

## Circuito RLC série

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{L \cdot C \cdot s^2 + R \cdot C \cdot s + 1}$$

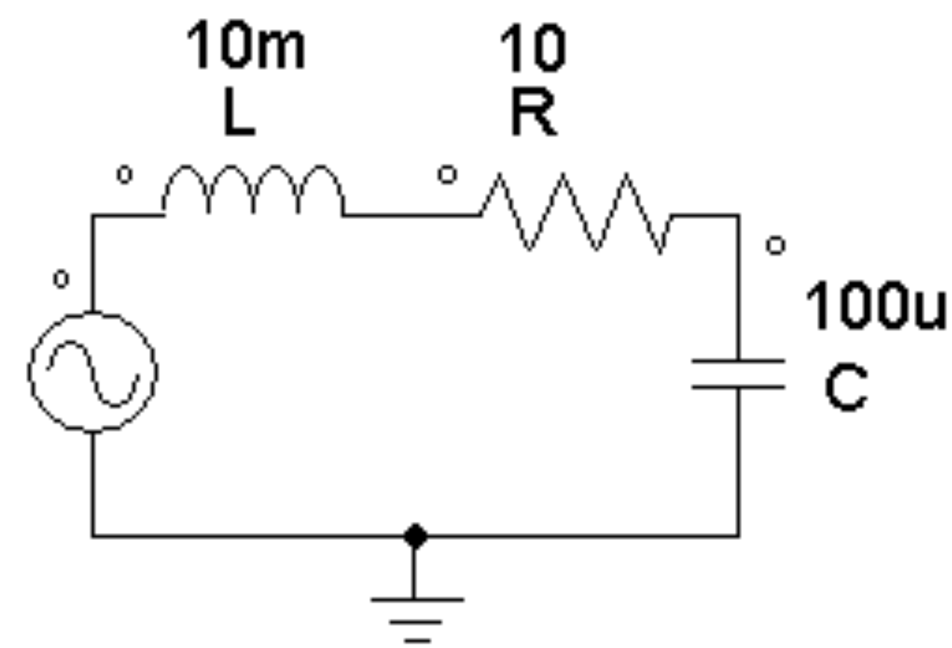


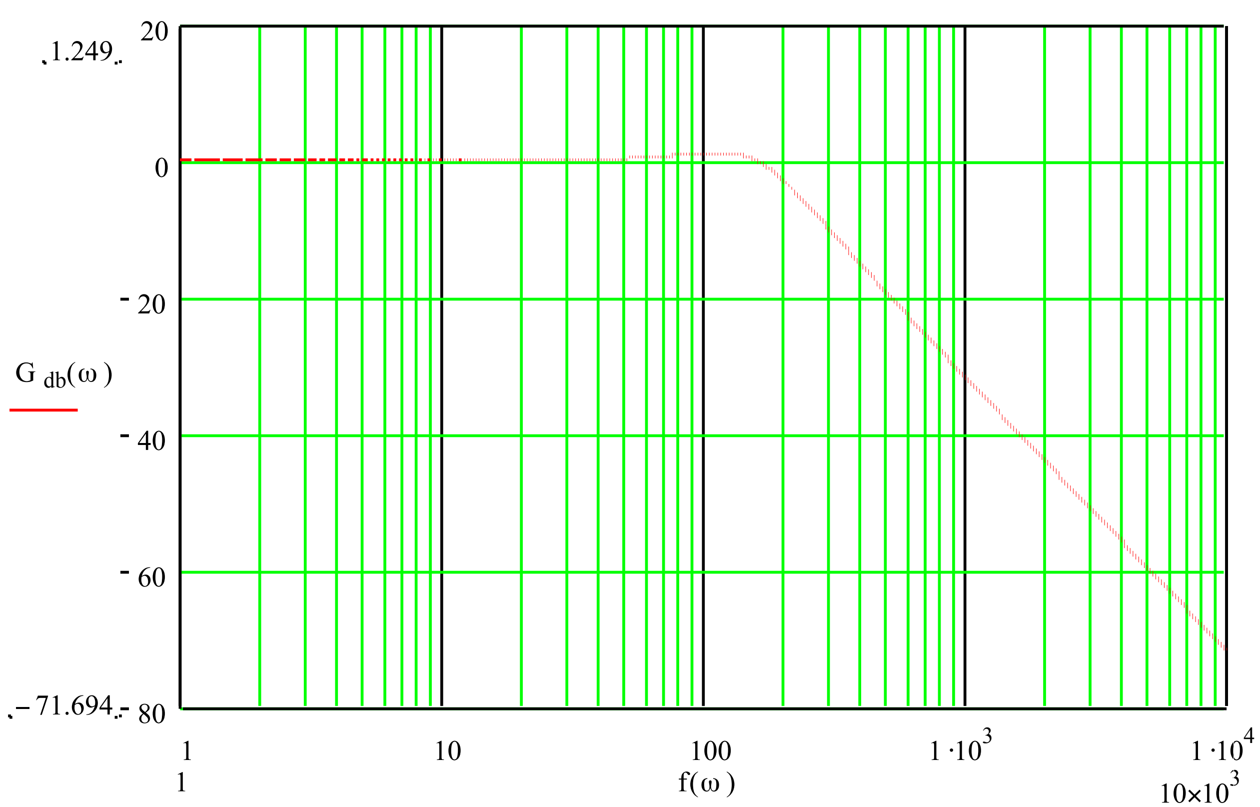
# Comportamento dos Componentes Passivos

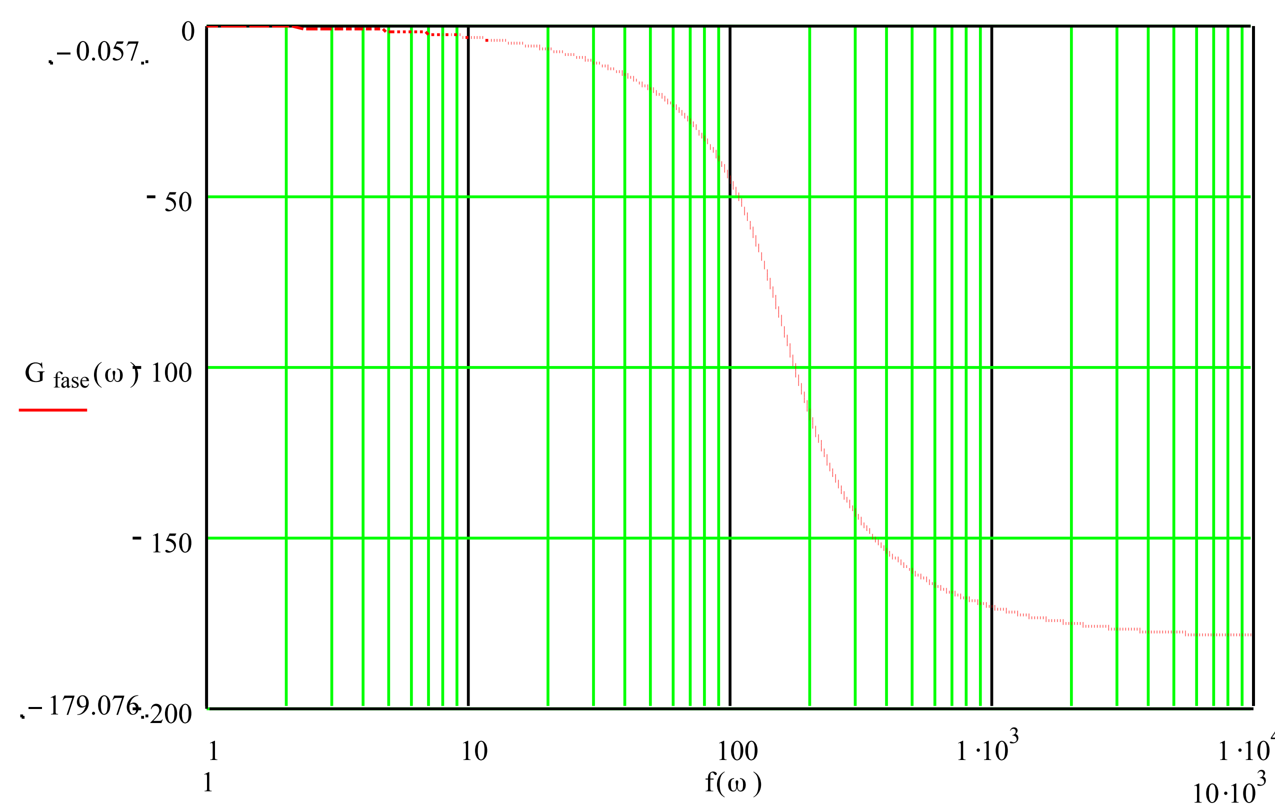
**Circuito RLC série**




$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{L \cdot C \cdot s^2 + R \cdot C \cdot s + 1}$$

**Diagrama de Bode**



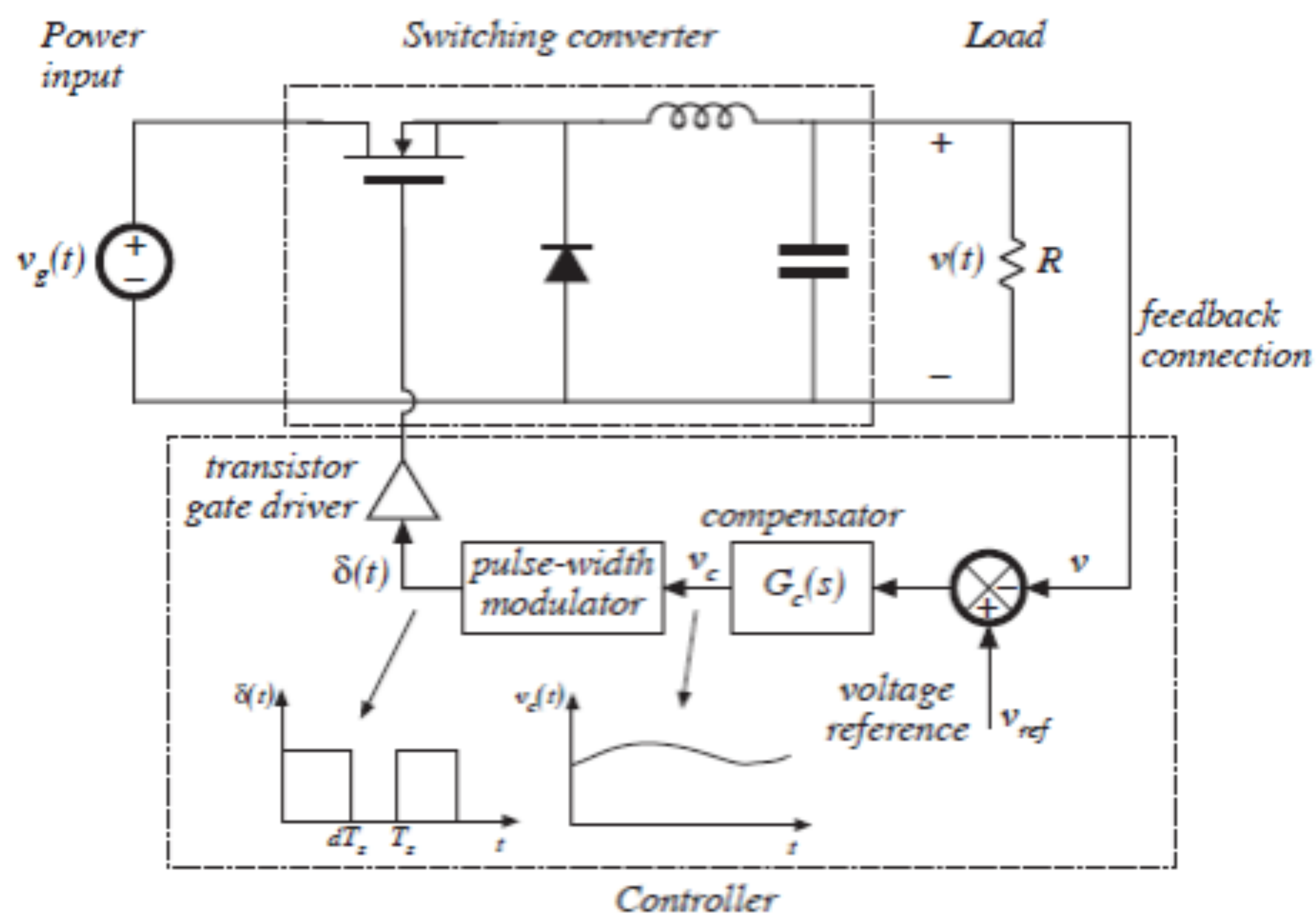



# Função de Transferência dos Conversores

$$\hat{v}(s) = G_{vd}(s)\,\hat{d}(s) + G_{vg}(s)\,\hat{v}_g(s)$$

$$G_{vd}(s) = \left.\frac{\hat{v}(s)}{\hat{d}(s)}\right|_{\hat{v}_g(s)=0}$$

$$G_{vg}(s) = \left.\frac{\hat{v}(s)}{\hat{v}_g(s)}\right|_{\hat{d}(s)=0}$$



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# Função de Transferência dos Conversores

$$\hat{v}(s) = G_{vd}(s)\,\hat{d}(s) + G_{vg}(s)\,\hat{v}_g(s)$$

Standard form:

$$G_{vd}(s) = \left.\frac{\hat{v}(s)}{\hat{d}(s)}\right|_{\hat{v}_g(s)=0}$$

$$G_{vd}(s) = G_{d0}\,\frac{\left(1 - \frac{s}{\omega_z}\right)}{\left(1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2\right)}$$

$$G_{vg}(s) = \left.\frac{\hat{v}(s)}{\hat{v}_g(s)}\right|_{\hat{d}(s)=0}$$

$$G_{vg}(s) = G_{g0}\,\frac{1}{1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$

# Função de Transferência dos Conversores

Standard form:

$$G_{vd}(s) = G_{d0}\frac{\left(1-\frac{s}{\omega_z}\right)}{\left(1+\frac{s}{Q\omega_0}+\left(\frac{s}{\omega_0}\right)^2\right)}$$

$$G_{vg}(s) = G_{g0}\frac{1}{1+\frac{s}{Q\omega_0}+\left(\frac{s}{\omega_0}\right)^2}$$

$$G_{d0} = -\frac{V_g - V}{D'^2} = -\frac{V_g}{D'^3} = \frac{V}{D\,D'^2}$$

$$\omega_z = \frac{V_g - V}{L\,I} = \frac{D'\,R}{D\,L} \qquad \text{(RHP)}$$

$$\omega_0 = \frac{D'}{\sqrt{LC}}$$

$$Q = D'R\sqrt{\frac{C}{L}}$$

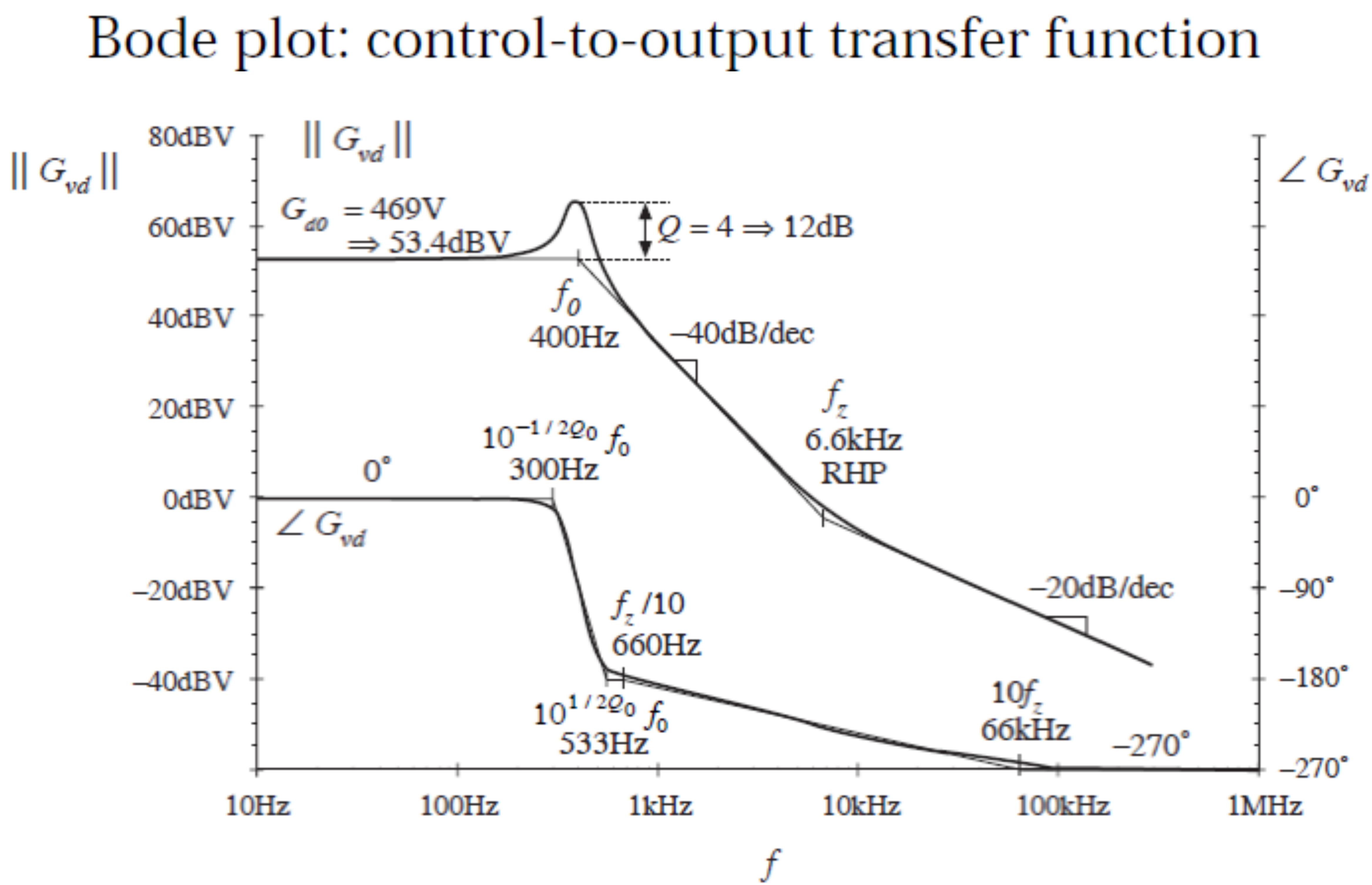
# Função de Transferência dos Conversores

Exemplo numérico - conversor Buck-Boost:

$$D = 0.6$$
$$R = 10\Omega$$
$$V_g = 30\text{V}$$
$$L = 160\mu\text{H}$$
$$C = 160\mu\text{F}$$

$$\left|G_{g0}\right| = \frac{D}{D'} = 1.5 \Rightarrow 3.5\text{dB}$$
$$\left|G_{d0}\right| = \frac{\left|V\right|}{D\,D'^2} = 469\text{V} \Rightarrow 53.4\text{dBV}$$
$$f_0 = \frac{\omega_0}{2\pi} = \frac{D'}{2\pi\sqrt{LC}} = 400\text{Hz}$$
$$Q = D'R\sqrt{\frac{C}{L}} = 4 \Rightarrow 12\text{dB}$$
$$f_z = \frac{\omega_z}{2\pi} = \frac{D'R}{2\pi DL} = 6.6\text{kHz}$$

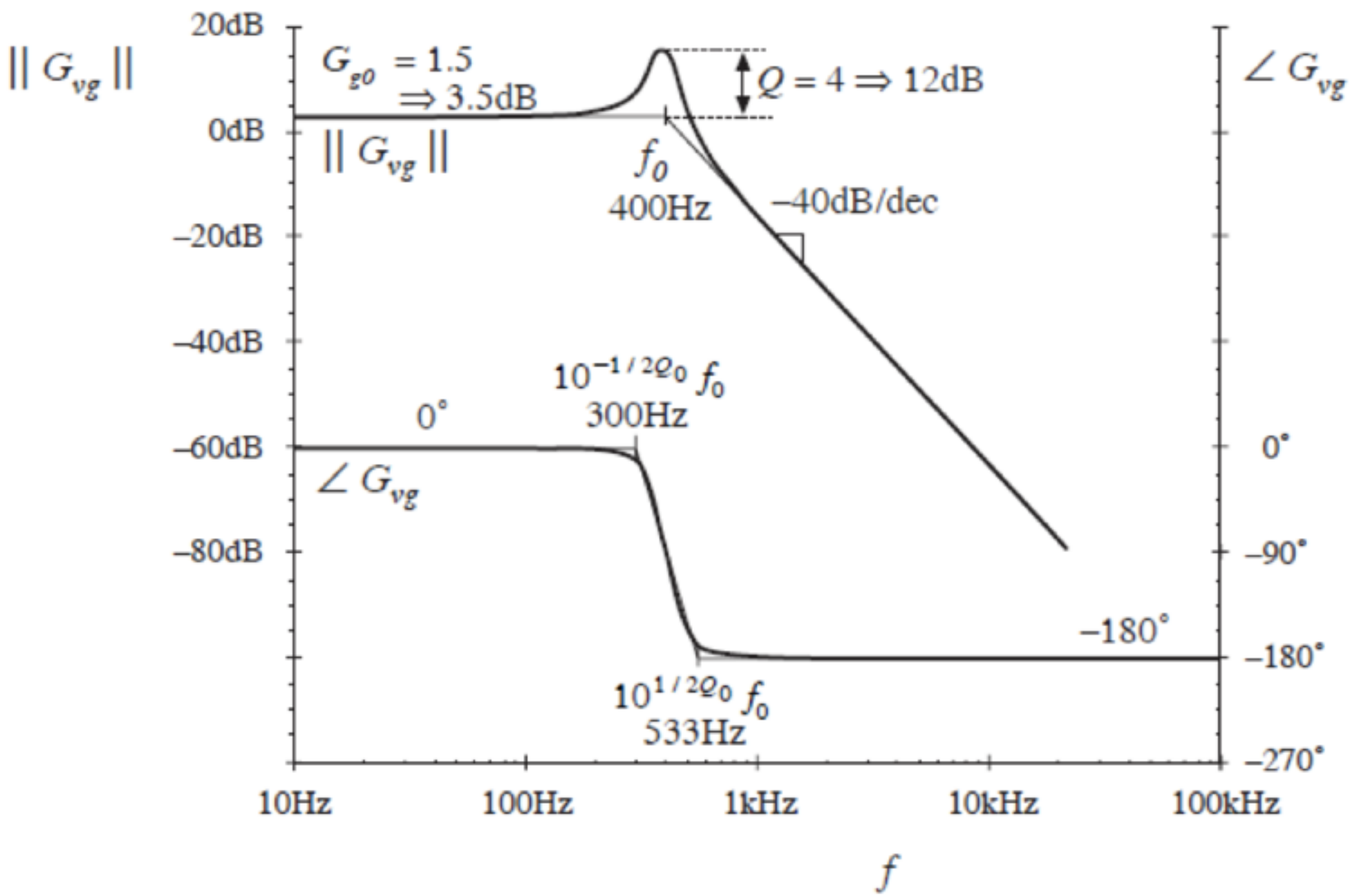
**Exemplo numérico - conversor Buck-Boost:**



# Função de Transferência dos Conversores

**Exemplo numérico - conversor Buck-Boost:**

## Bode plot: line-to-output transfer function



# Função de Transferência dos Conversores

*Table 8.2. Salient features of the small-signal CCM transfer functions of some basic dc-dc converters*

| Converter | $G_{g0}$ | $G_{d0}$ | $\omega_0$ | $Q$ | $\omega_z$ |
|---|---|---|---|---|---|
| buck | $D$ | $\frac{V}{D}$ | $\frac{1}{\sqrt{LC}}$ | $R\sqrt{\frac{C}{L}}$ | $\infty$ |
| boost | $\frac{1}{D'}$ | $\frac{V}{D'}$ | $\frac{D'}{\sqrt{LC}}$ | $D'R\sqrt{\frac{C}{L}}$ | $\frac{D'^2R}{L}$ |
| buck-boost | $-\frac{D}{D'}$ | $\frac{V}{D\,D'^2}$ | $\frac{D'}{\sqrt{LC}}$ | $D'R\sqrt{\frac{C}{L}}$ | $\frac{D'^2R}{D\,L}$ |

where the transfer functions are written in the standard forms

$$G_{vd}(s) = G_{d0}\frac{\left(1 - \frac{s}{\omega_z}\right)}{\left(1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2\right)}$$

$$G_{vg}(s) = G_{g0}\frac{1}{1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$

# Função de Transferência dos Conversores

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## Usando Modelo da Chave PWM de Vorpérian:

### Simplified Analysis of PWM Converters Using Model of PWM Switch Part I: Continuous Conduction Mode

VATCHÉ VORPÉRIAN
Virginia Polytechnic Institute and State University

**A circuit-oriented approach to the analysis of pulsewidth modulation (PWM) converters is presented. This method relies on the identification of a three-terminal nonlinear device, called the PWM switch, which consists of only the active and passive switches in a PWM converter. Once the invariant properties of the PWM switch are determined, an average equivalent circuit model for it can be derived. This model is versatile enough that it can easily account for storage-time modulation of BJTs. The dc and small-signal characteristics of a large class of PWM converters can then be obtained by a simple substitution of the PWM switch with its equivalent circuit model. The methodology presented is very similar to linear amplifier circuit analysis whereby the transistor is replaced by its equivalent circuit model. Consequently, for the novice, this method should serve as a very smooth introduction to the analysis of PWM converters.**

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0018-9251/90/0500-0490 $1.00 © 1990 IEEE

INTRODUCTION

In this article the concept of the pulsewidth modulation (PWM) switch is introduced which leads to considerable simplification in the analysis (linear and nonlinear) and generation of dc-to-dc converters. To show the simplicity and elegance of the *PWM switch model* the dc and small-signal analysis of basic dc-to-dc converters is given. Of course, the results of the dc and small-signal analysis of dc-to-dc PWM converters are well known today from the *systematic* method of state-space averaging and its *canonical circuit model* [1, 2]. Hence, before going any further, a brief description of the two models mentioned above is given and the *difference* in the analytical approach between them is explained in order to justify the purpose of this article. First, the *canonical circuit model* completely represents the dc and small-signal characteristics of a PWM converter and is obtained after a considerable amount of matrix manipulations in order to single out the desirable input and output characteristics of the converter (input impedance, line-to-output transfer function, and output impedance) in addition to its control-to-output characteristics. The *PWM switch model*, on the other hand, represents only the dc and small-signal characteristics of the nonlinear part of the converter, which consists of the active and passive switches (the PWM switch), and is obtained after a few lines of very simple algebra. The dc and small-signal characteristics of a PWM converter are then obtained by replacing the PWM switch with its equivalent circuit model in a manner similar to obtaining the small-signal characteristics of linear amplifiers whereby the transistor is replaced by its equivalent circuit model. There are two advantages in using the model of the PWM switch. First, the PWM switch model allows many PWM converters to be analyzed using simple linear electronic circuit analysis programs (P-SPICE, MICRO-CAP to name a few), which allow for user-defined models (macros), without recourse to special-purpose programs which manipulate state-space equations. The second and more important advantage is a *pedagogical* one. More and more universities are beginning to teach power electronics at the senior level in their undergraduate program. Although students at this level are familiar with some matrix algebra, it would be far easier for them to learn all about the dc and small-signal properties of PWM converters using the method of *equivalent circuit model* which they learned in their electronics courses earlier. Students spend quite a bit of time learning about the nonlinear characteristics of the transistor and its small-signal equivalent circuit model. They later use this model to analyze the small-signal characteristics of linear amplifiers simply by replacing the transistor with its equivalent circuit model. Why not do the same in power electronics? Ultimately, whether or not the PWM switch model presented here is a useful



### Simplified Analysis of PWM Converters Using Model of PWM Switch Part II: Discontinuous Conduction Mode

VATCHÉ VORPÉRIAN
Virginia Polytechnic Institute and State University

**According to the method of state-space averaging, when a pulsewidth modulation (PWM) converter enters discontinuous conduction mode, the inductor current state is lost from the average model of the converter. In this work, it is shown that there is neither theoretical nor experimental justification of the disappearance of the inductor state as claimed by the method of state-space averaging. For example, when the model of the PWM**

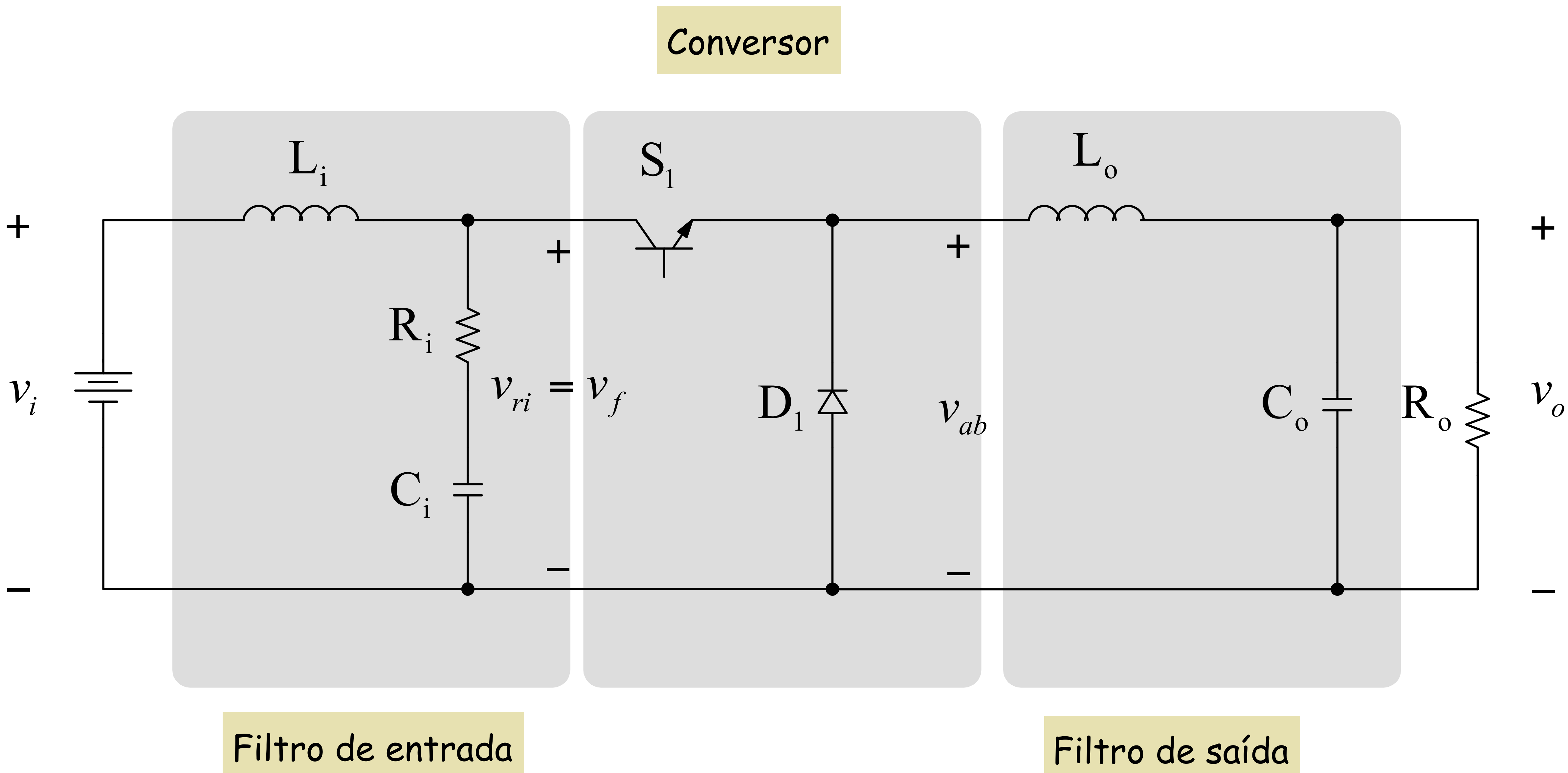
INTRODUCTION

In this article the model of the pulsewidth modulation (PWM) switch in discontinuous conduction mode (DCM) is developed and used in the analysis of PWM converters operating in DCM. As in the case of continuous conduction mode (CCM) [3], the model of the PWM switch in DCM represents the dc and small-signal characteristics of the nonlinear part of the converter which consists of the active and passive switch pair as shown in Fig. 1. In contrast to the model in CCM, the model of the PWM switch in DCM contains small-signal resistances which damp the low-pass filter to the point where two real poles are formed. The physical significance of these small-signal resistances is easy to understand as they represent the load dependent nature of the conversion ratio of these converters in DCM. The motivation and advantages behind the method of analysis presented here are discussed in Part I of this paper [3].

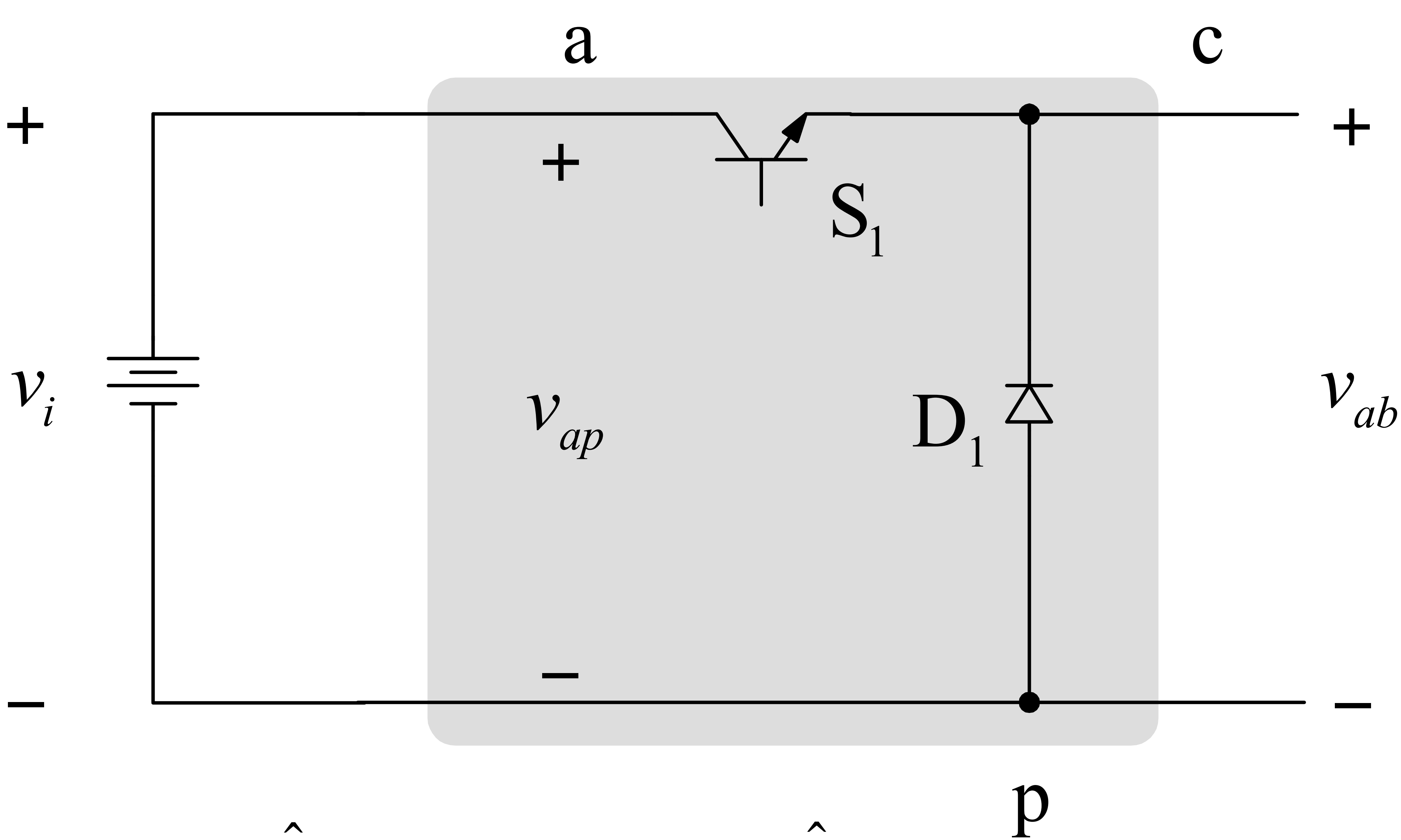
Whereas, use of the model of the PWM switch in CCM yields the *same* results as those given by the method of state-space averaging, in DCM the model of the PWM switch yields results which are *different* than those given by state-space averaging [1]. The fundamental difference between the two methods is that state-space averaging predicts that the discontinuous current state does not contribute to the order of the average model while the PWM switch

# Função de Transferência dos Conversores

**Exemplo completo de aplicação: Conversor Buck**

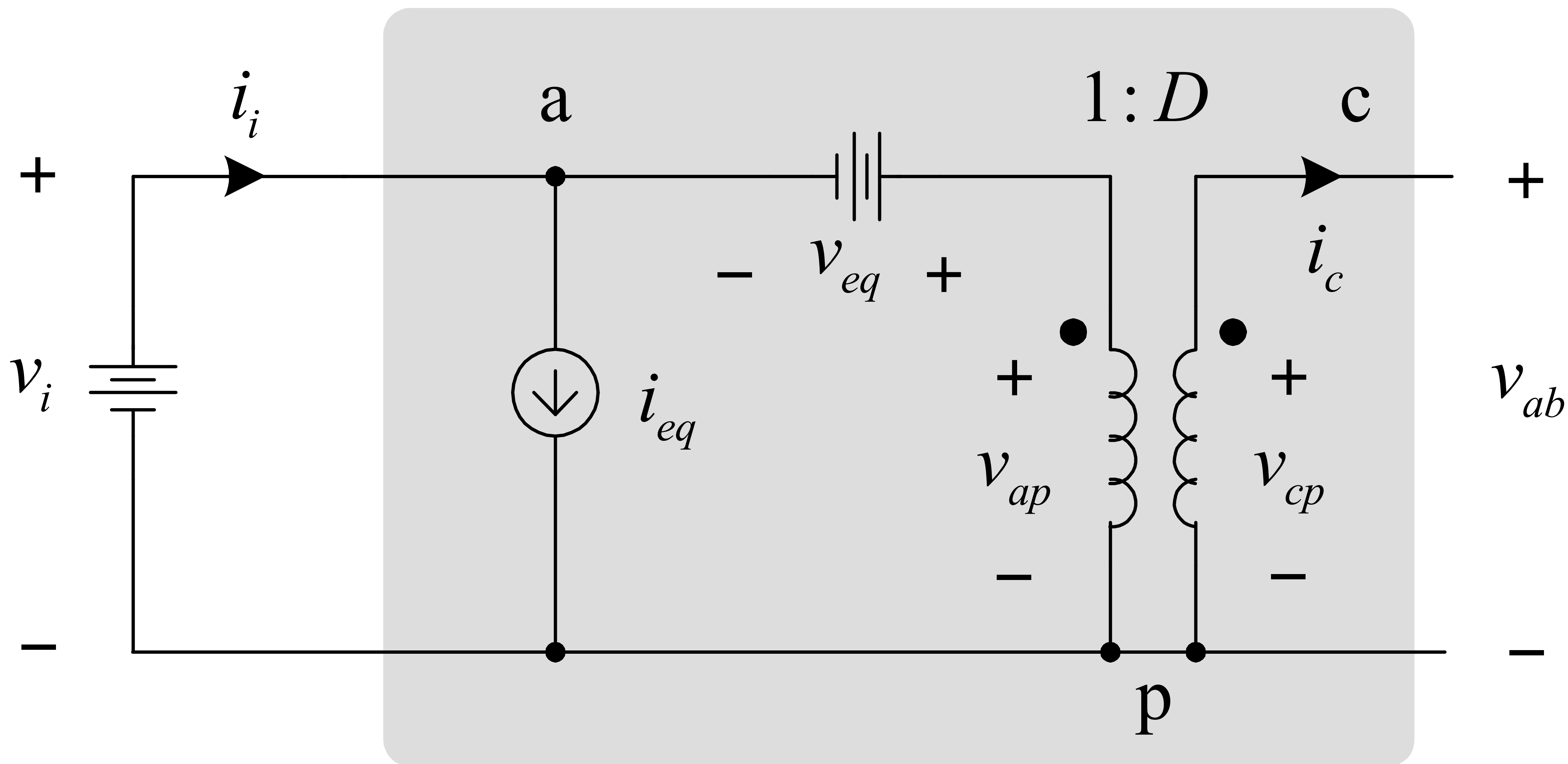


# Função de Transferência dos Conversores




$$G_1(s) = \frac{\hat{v}_{ab}}{\hat{d}} \qquad F_1(s) = \frac{\hat{v}_{ab}}{\hat{v}_i}$$

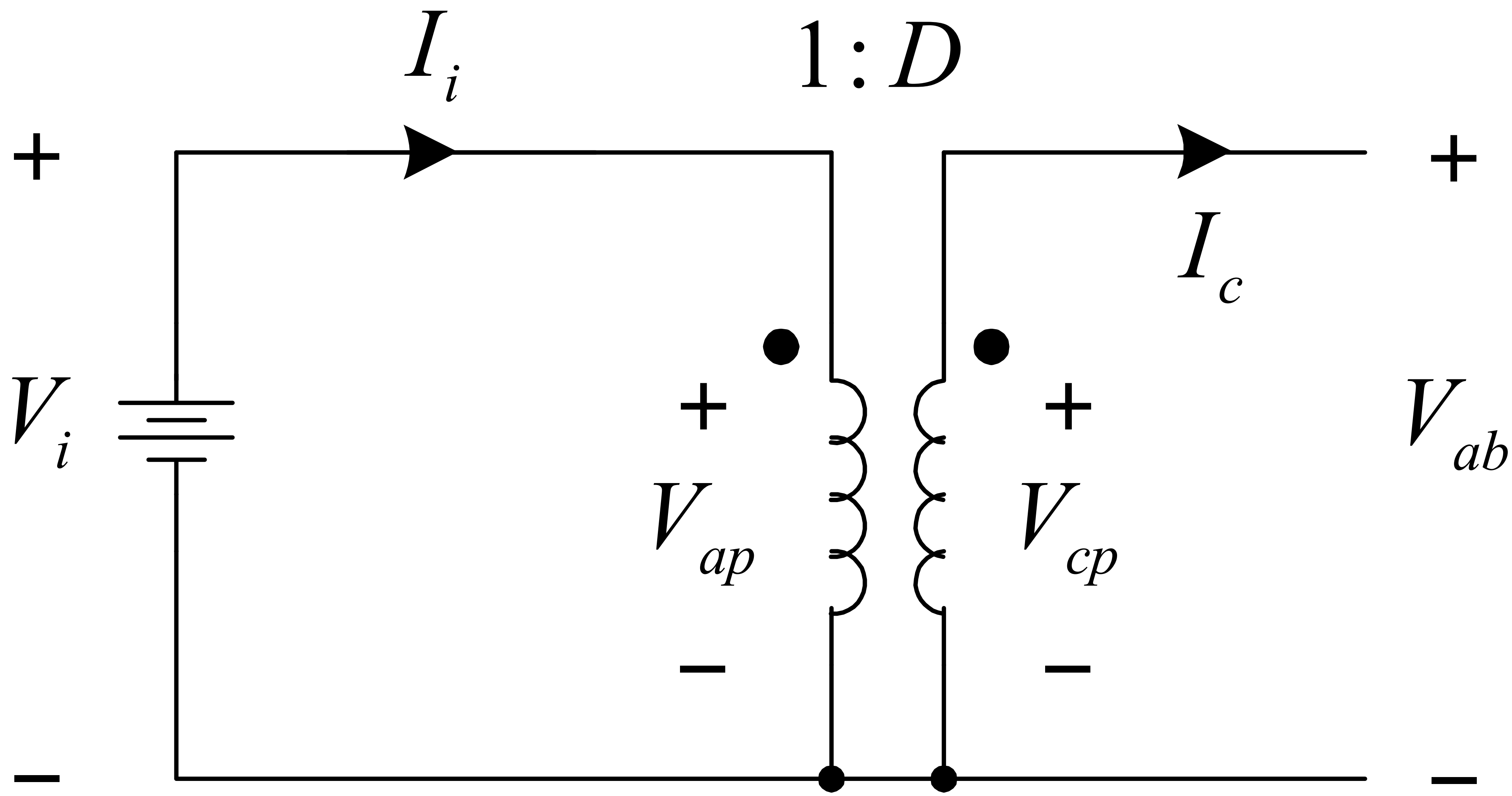
# Função de Transferência dos Conversores




$$f = F + \hat{f} \qquad i_{eq} = I_c \cdot \hat{d} \qquad v_{eq} = \frac{V_{ap}}{D} \cdot \hat{d}$$

## Função de Transferência dos Conversores

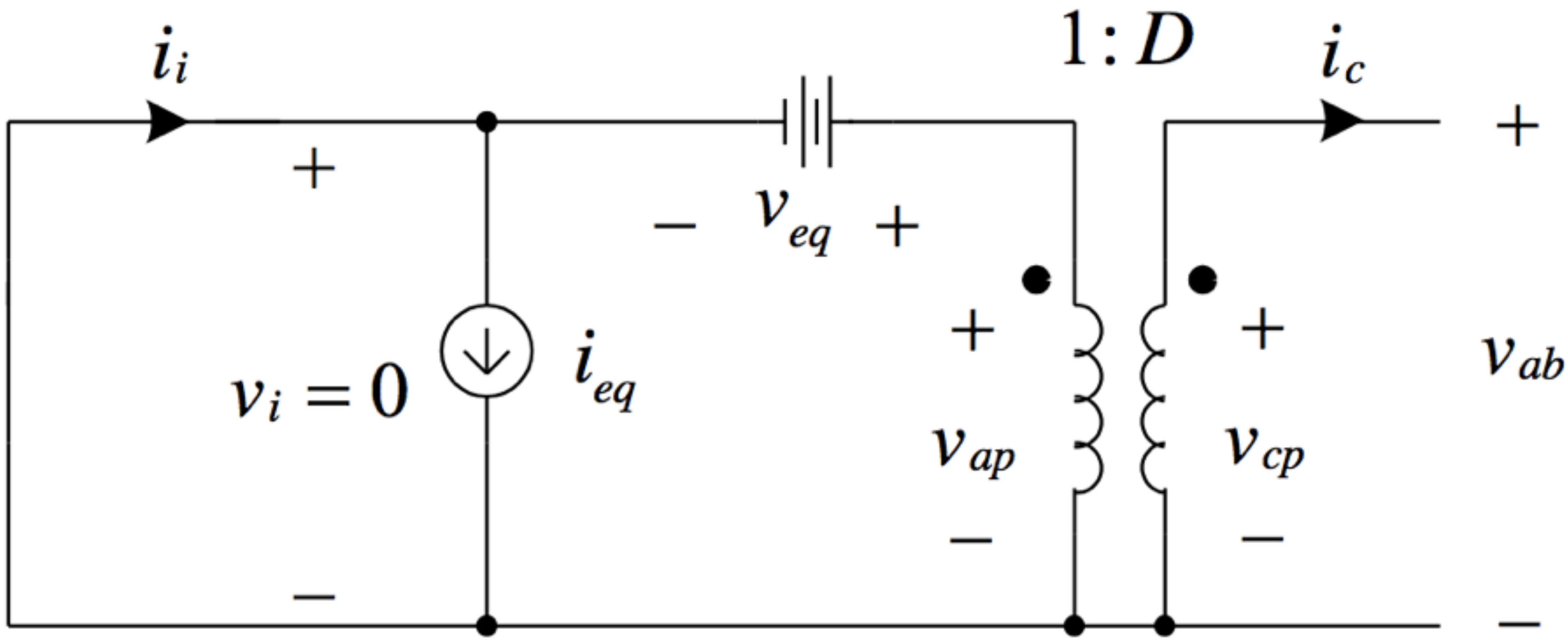
### Modelo de regime permanente




$$V_{ap} = V_i \qquad V_{cp} = D \cdot V_{ap} = D \cdot V_i \qquad V_{ab} = V_{cp} = D \cdot V_i \qquad I_o = \frac{I_i}{D}$$

# Função de Transferência dos Conversores

Modelo de pequenos sinais para determinar G(s):




$$\hat{v}_{ap} = v_{eq} = \frac{V_{ap}}{D} \cdot \hat{d}$$

$$\hat{v}_{ap} = \frac{V_i}{D} \cdot \hat{d}$$

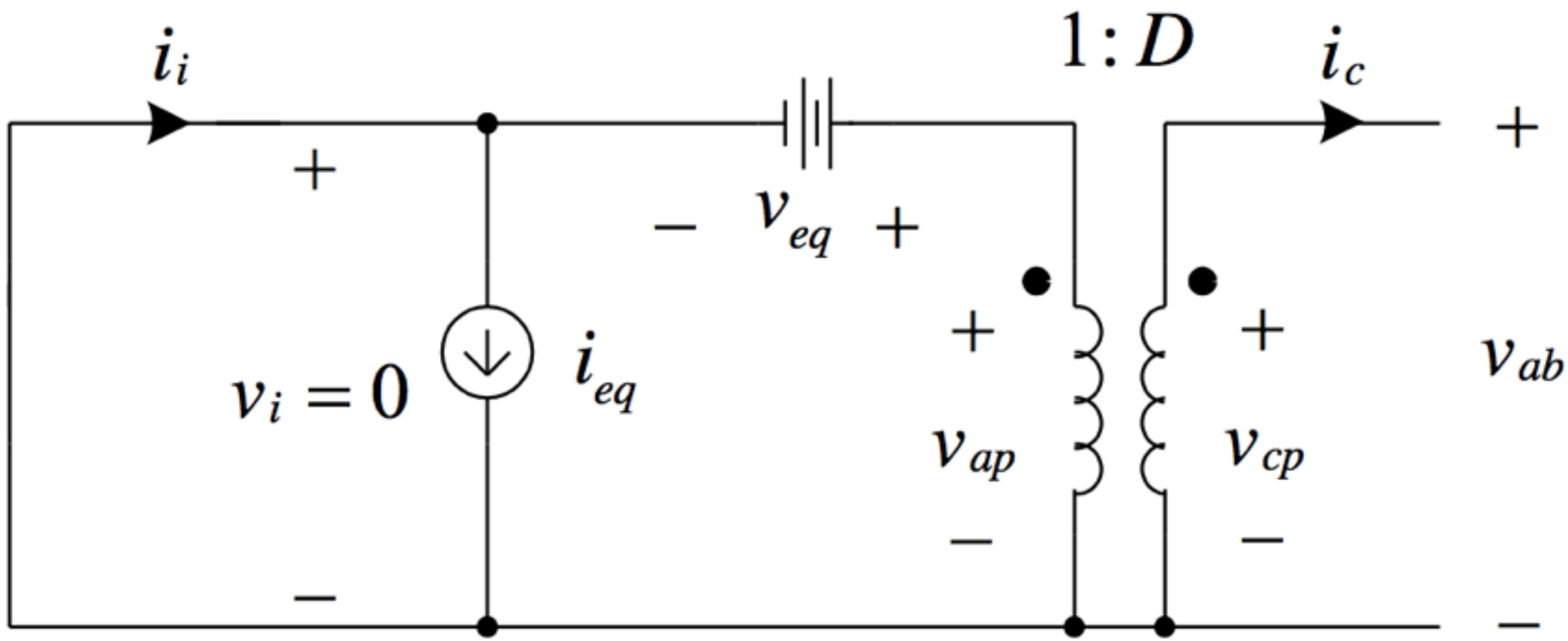
$$\hat{v}_{cp} = D \cdot \hat{v}_{ap} = D \cdot \frac{V_i}{D} \cdot \hat{d} = V_i \cdot \hat{d}$$

$$V_{ap} = V_i$$

$$\hat{v}_{ab} = \hat{v}_{cp} = V_i \cdot \hat{d}$$

# Função de Transferência dos Conversores

Modelo de pequenos sinais para determinar G(s):



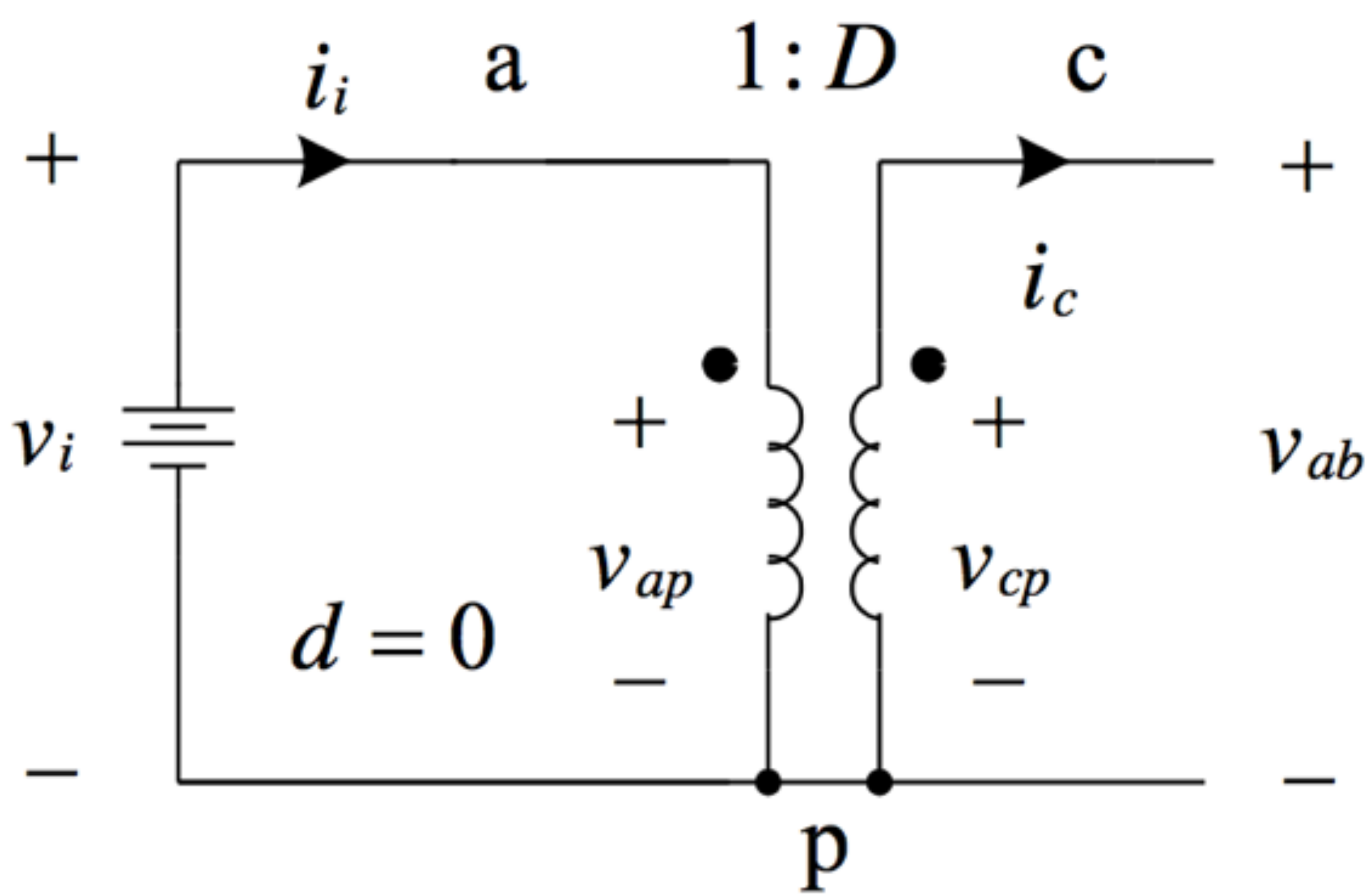

$$\hat{v}_{ab} = \hat{v}_{cp} = V_i \cdot \hat{d}$$

$$G_1(s) = \frac{\hat{v}_{ab}}{\hat{d}} = V_i$$

Note que $i_i$ não interfere em G(s).

# Função de Transferência dos Conversores

Modelo de pequenos sinais para determinar F(s):



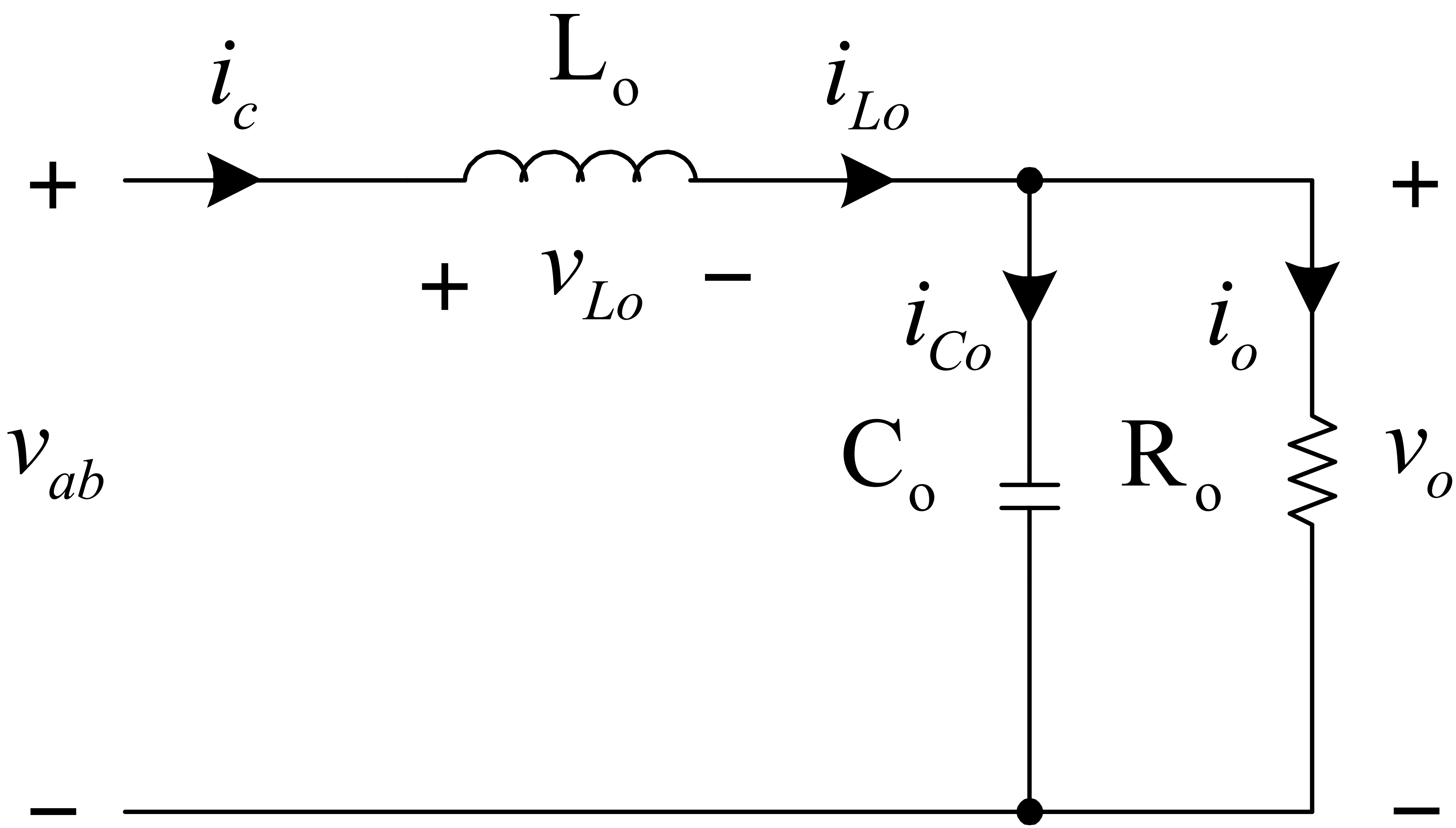

$$\hat{v}_{cp} = D \cdot \hat{v}_{ap} = D \cdot \hat{v}_i$$

$$\hat{v}_{ab} = \hat{v}_{cp} = D \cdot \hat{v}_i$$

$$F_1(s) = \frac{\hat{v}_{ab}}{\hat{v}_i} = D$$

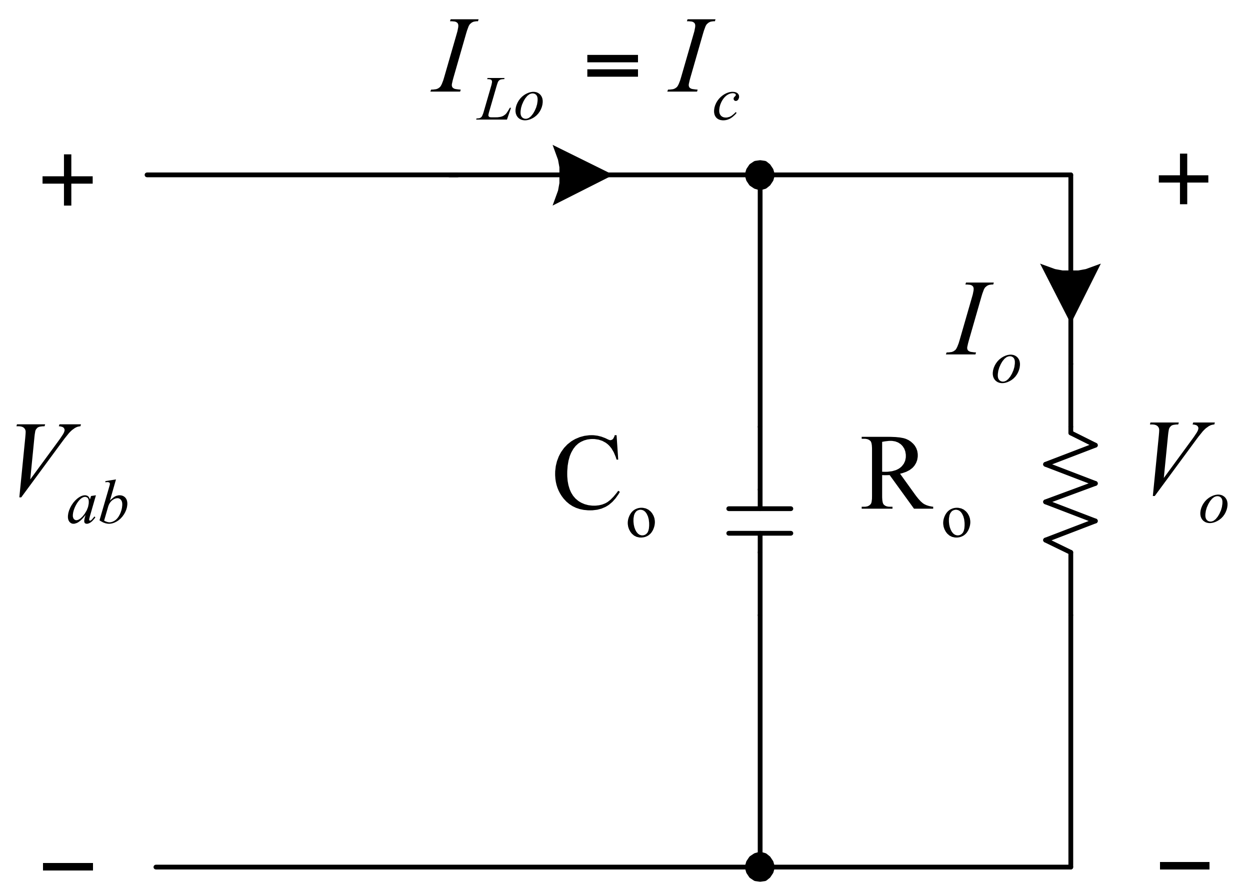
Note que $i_i$ não interfere em F(s).

# Função de Transferência dos Conversores



# Função de Transferência dos Conversores

## Modelo de regime permanente



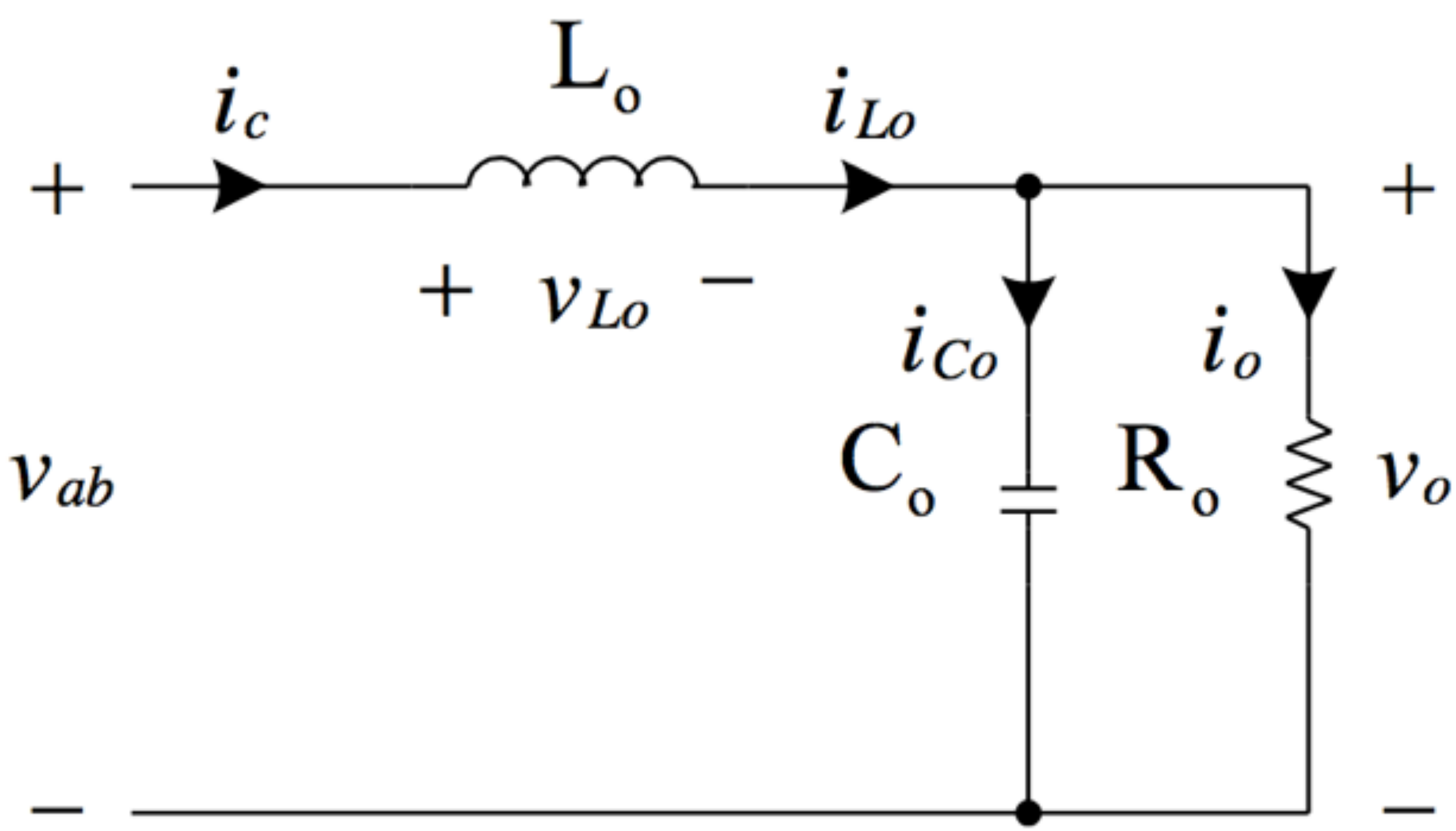

$$V_o = V_{ab}$$

$$I_o = \frac{V_o}{R_o}$$

$$I_{Lo} = I_o = I_c = \frac{V_o}{R_o}$$

# Função de Transferência dos Conversores

Modelo de pequenos sinais para determinar G(s):




$$\hat{v}_{ab} = \hat{v}_{Lo} + \hat{v}_o$$

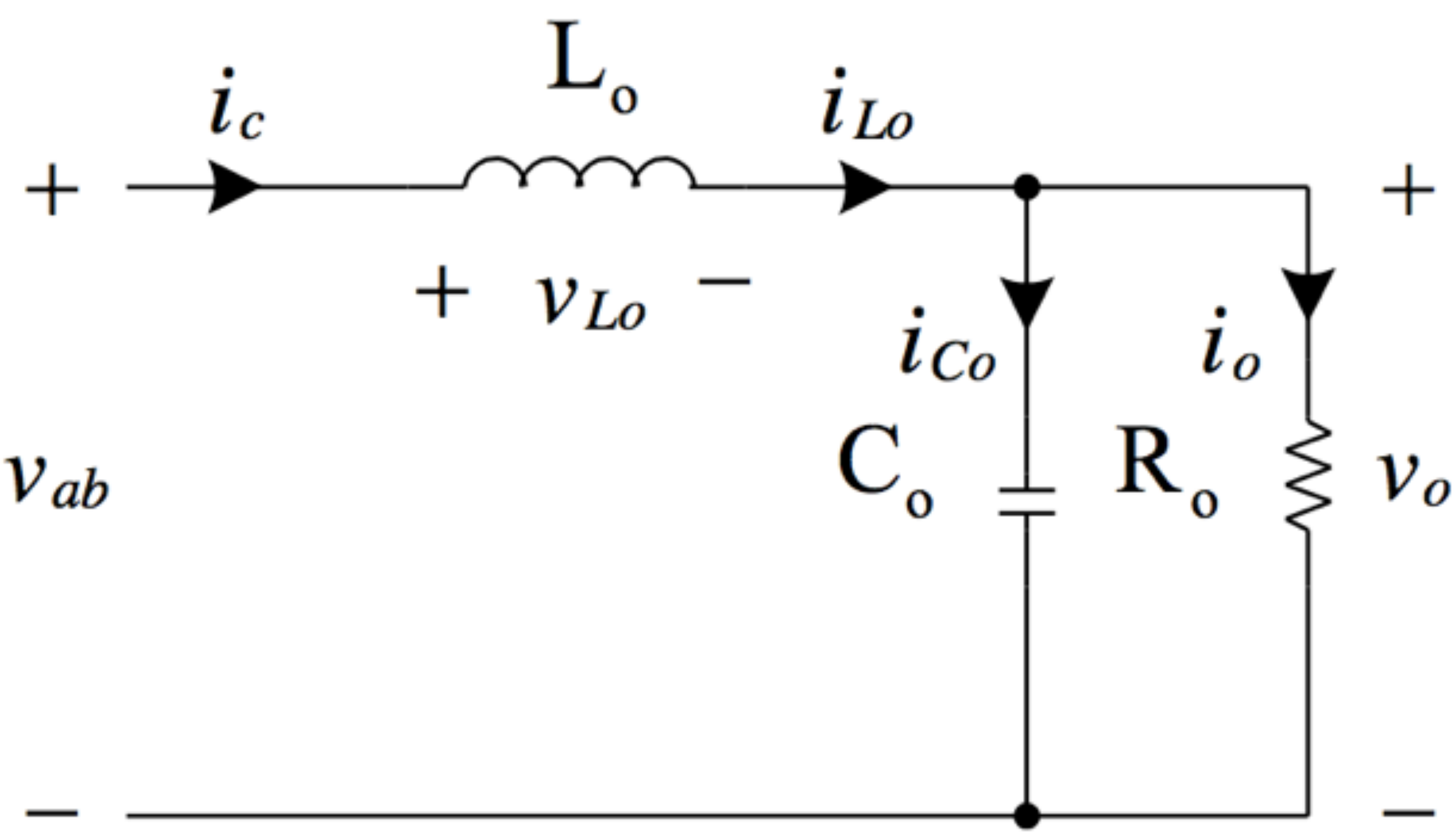
$$\hat{v}_{Lo} = s \cdot L_o \cdot \hat{i}_{Lo}$$

$$\hat{i}_o = \frac{\hat{v}_o}{R_o}$$

$$\hat{v}_{ab} = s \cdot L_o \cdot \hat{i}_{Lo} + \frac{\hat{v}_o}{R_o}$$

# Função de Transferência dos Conversores

## Modelo de pequenos sinais para determinar G(s):




$$\hat{i}_{Lo} = \hat{i}_{Co} + \hat{i}_o$$

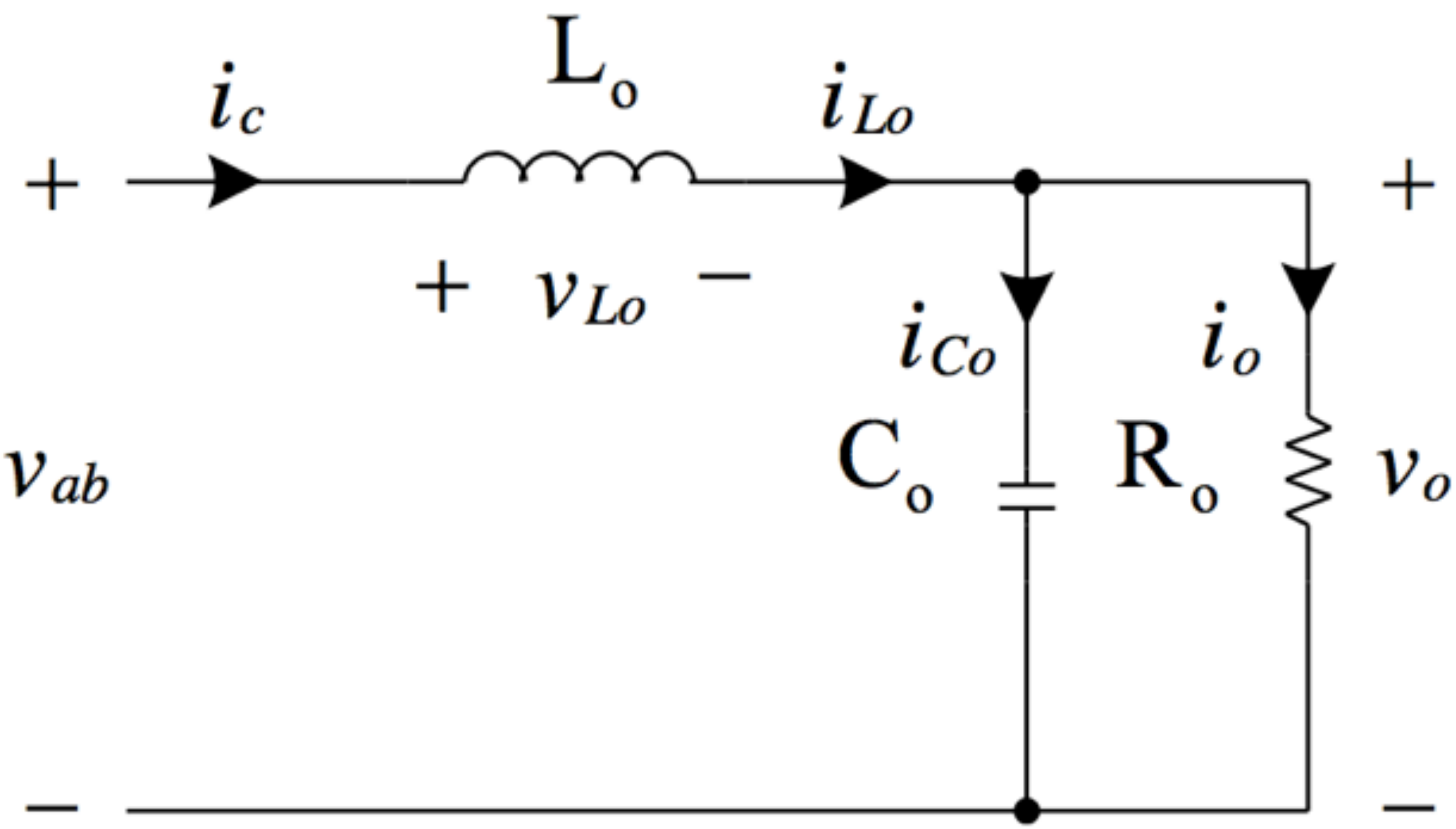
$$\hat{i}_{Lo} = s \cdot C_o \cdot \hat{v}_o + \frac{v_o}{R_o}$$

$$\hat{i}_{Co} = s \cdot C_o \cdot \hat{v}_o$$

$$\hat{v}_{ab} = s \cdot L_o \cdot \left( s \cdot C_o \cdot \hat{v}_o + \frac{\hat{v}_o}{R_o} \right) + \hat{v}_o$$

# Função de Transferência dos Conversores

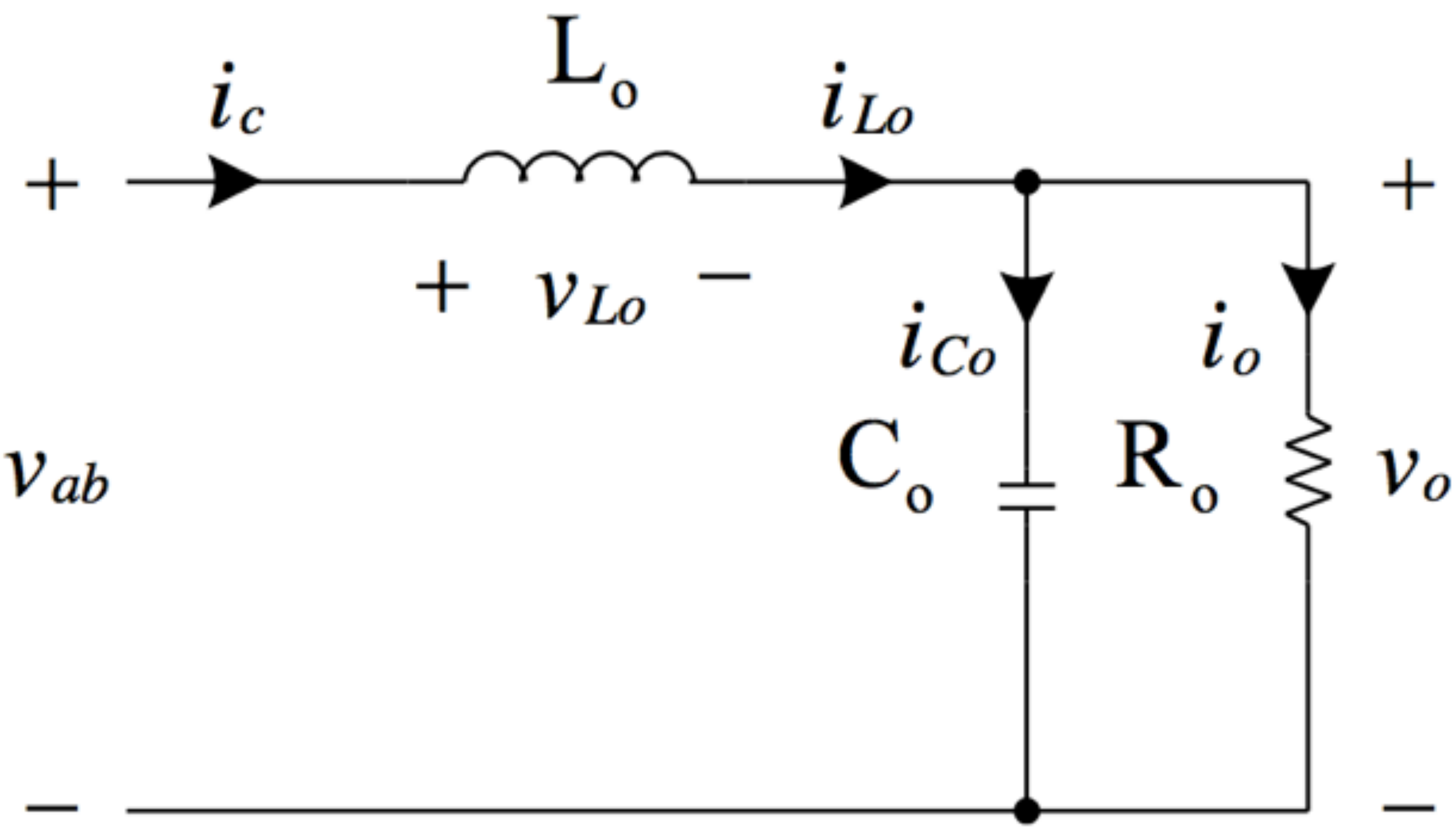
Modelo de pequenos sinais para determinar G(s):




$$G_2(s) = \frac{\hat{v}_o}{\hat{v}_{ab}} = \frac{R_o}{s^2 \cdot L_o \cdot C_o \cdot R_o + s \cdot L_o + R_o}$$

# Função de Transferência dos Conversores

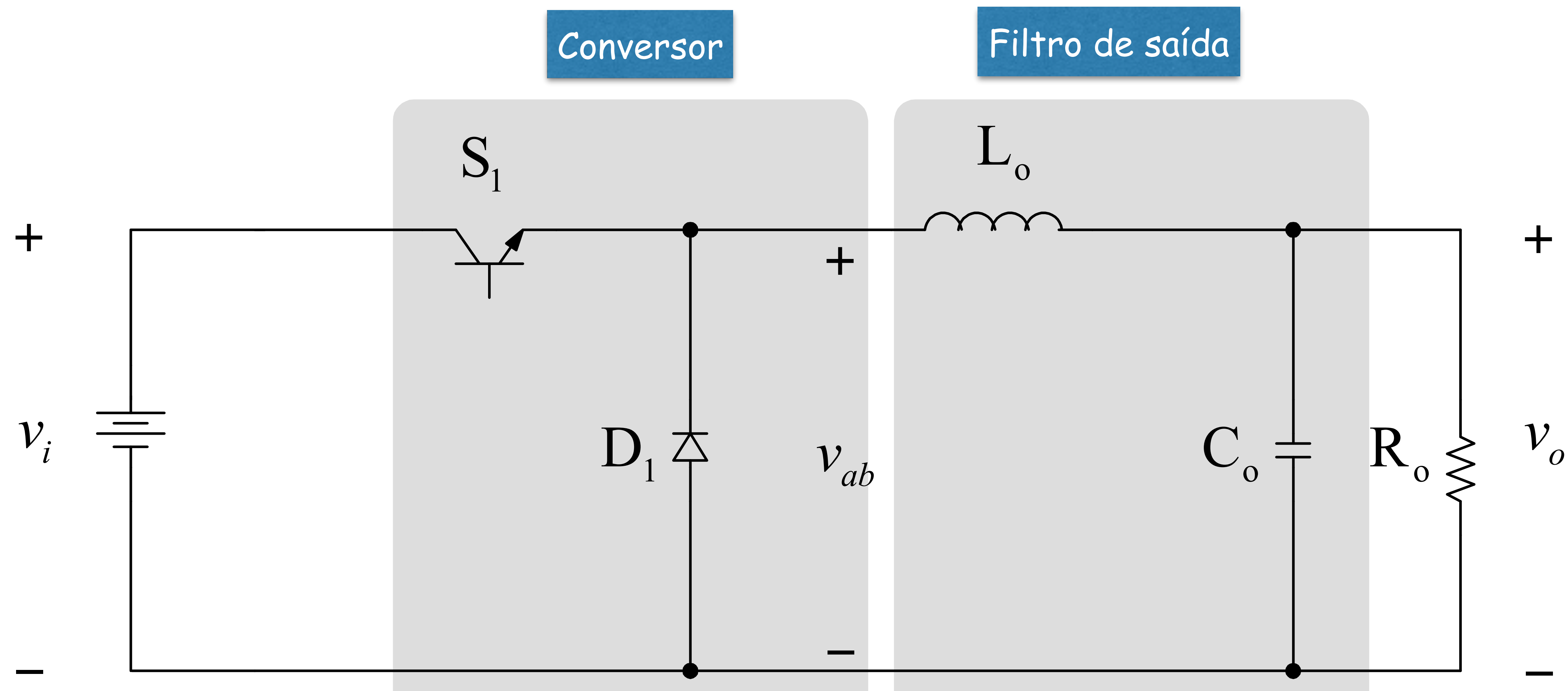
## Modelo de pequenos sinais para determinar F(s):




$$F_2(s) = \frac{\hat{v}_o}{\hat{v}_{ab}} = \frac{R_o}{s^2 \cdot L_o \cdot C_o \cdot R_o + s \cdot L_o + R_o}$$

# Função de Transferência dos Conversores

## Função de transferência da tensão de saída pela razão cíclica G(s):

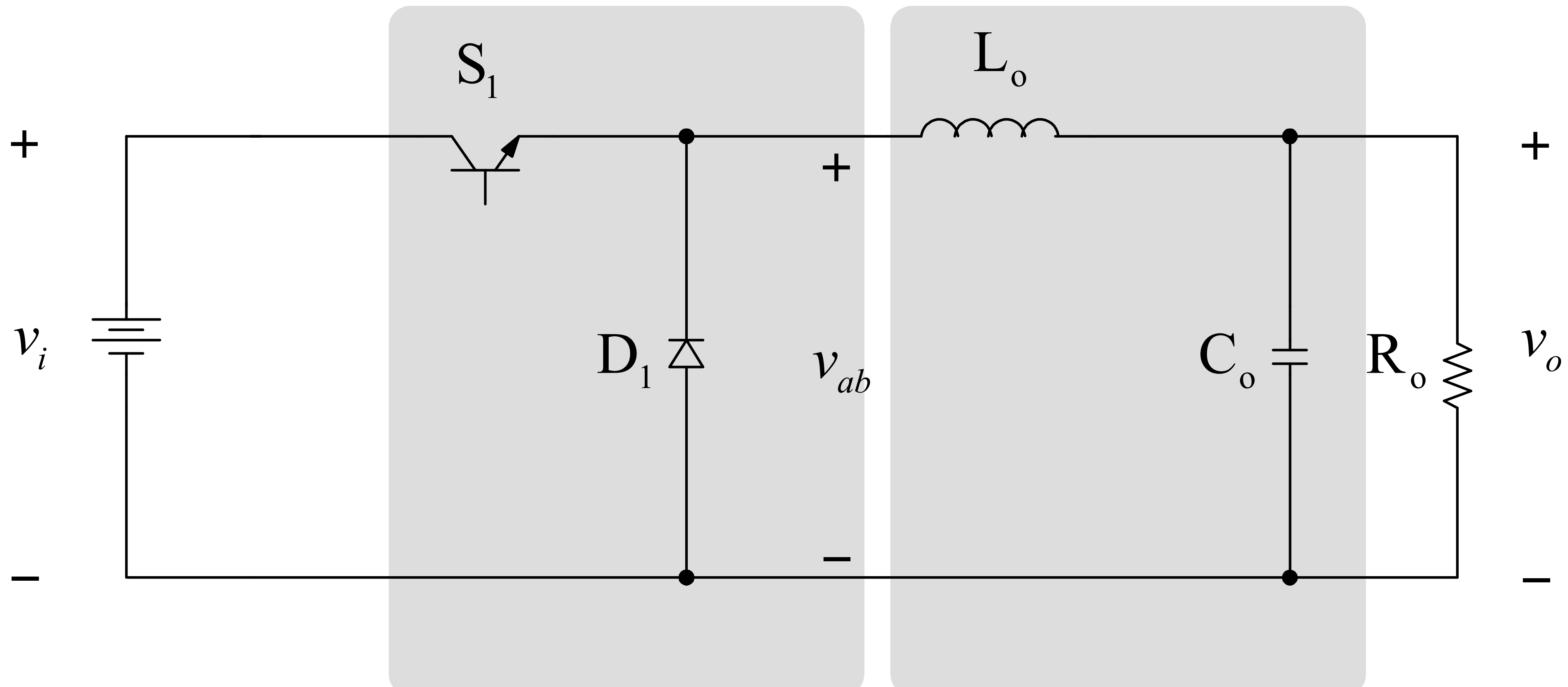



$$G_1(s) = \frac{\hat{v}_{ab}}{\hat{d}}$$

$$G_2(s) = \frac{\hat{v}_o}{\hat{v}_{ab}}$$

# Função de Transferência dos Conversores

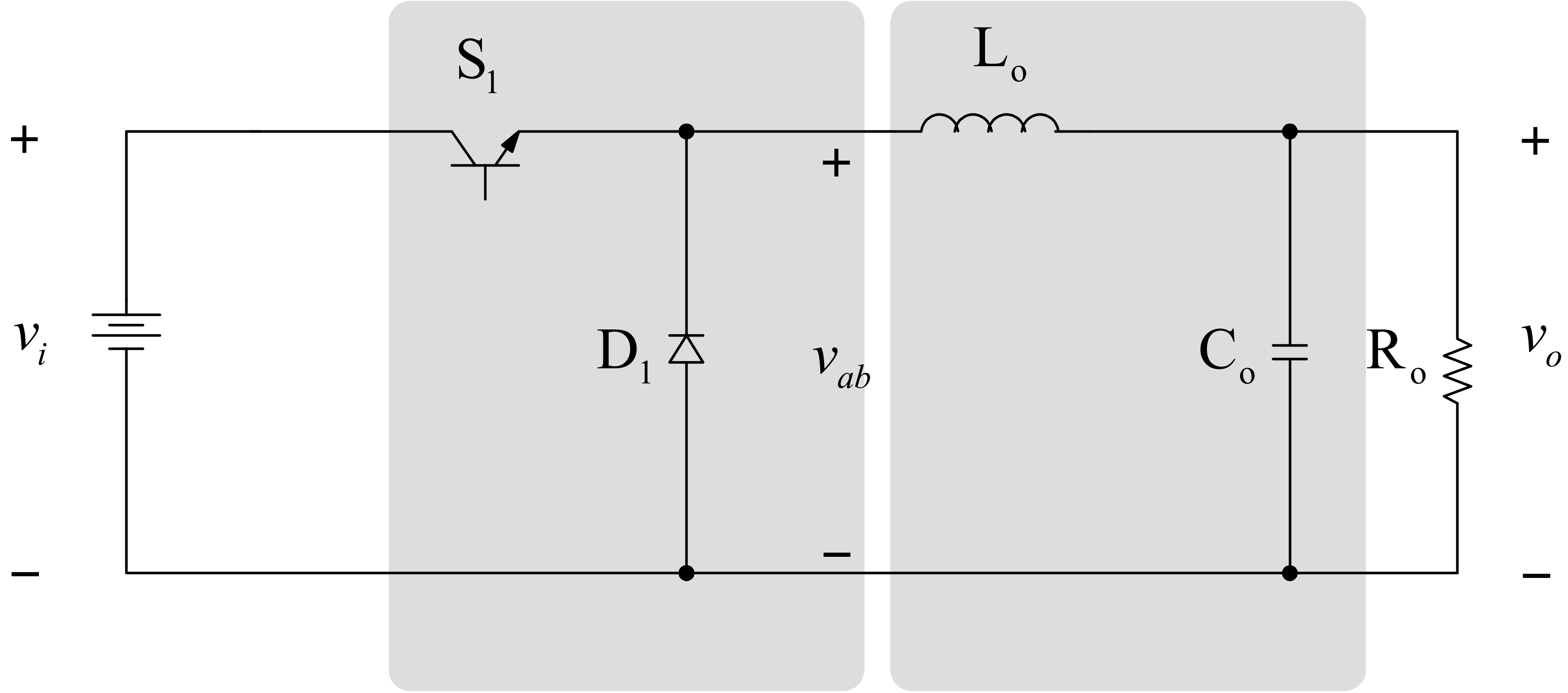
## Função de transferência da tensão de saída pela razão cíclica G(s):




$$G(s)=G_1(s)\cdot G_2(s)=\frac{\hat{v}_{ab}}{\hat{d}}\cdot\frac{\hat{v}_o}{\hat{v}_{ab}}=\frac{\hat{v}_o}{\hat{d}}=V_i\cdot\frac{R_o}{s^2\cdot L_o\cdot C_o\cdot R_o+s\cdot L_o+R_o}$$

# Função de Transferência dos Conversores

## Função de transferência da tensão de saída pela razão cíclica G(s):

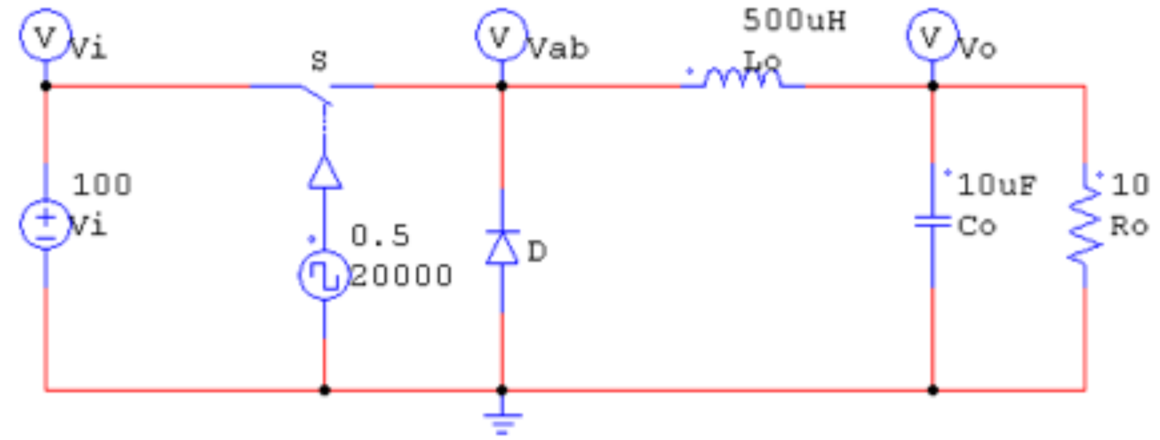


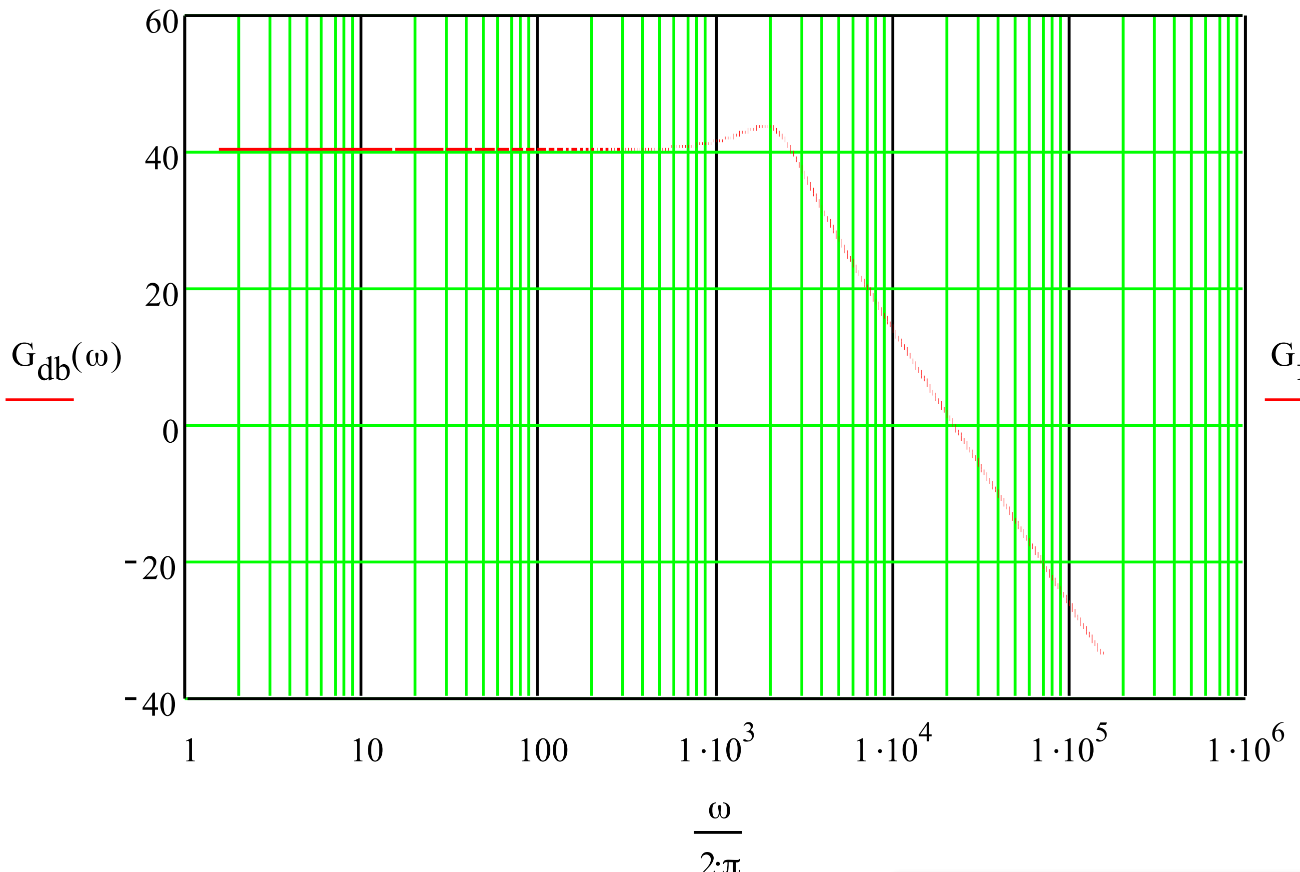

$$G(s) = \frac{V_i \cdot R_o}{s^2 \cdot L_o \cdot C_o \cdot R_o + s \cdot L_o + R_o}$$

# Função de Transferência dos Conversores

Função de transferência da tensão de saída pela razão cíclica G(s):

$$G(s)=\frac{V_i\cdot R_o}{s^2\cdot L_o\cdot C_o\cdot R_o+s\cdot L_o+R_o}$$



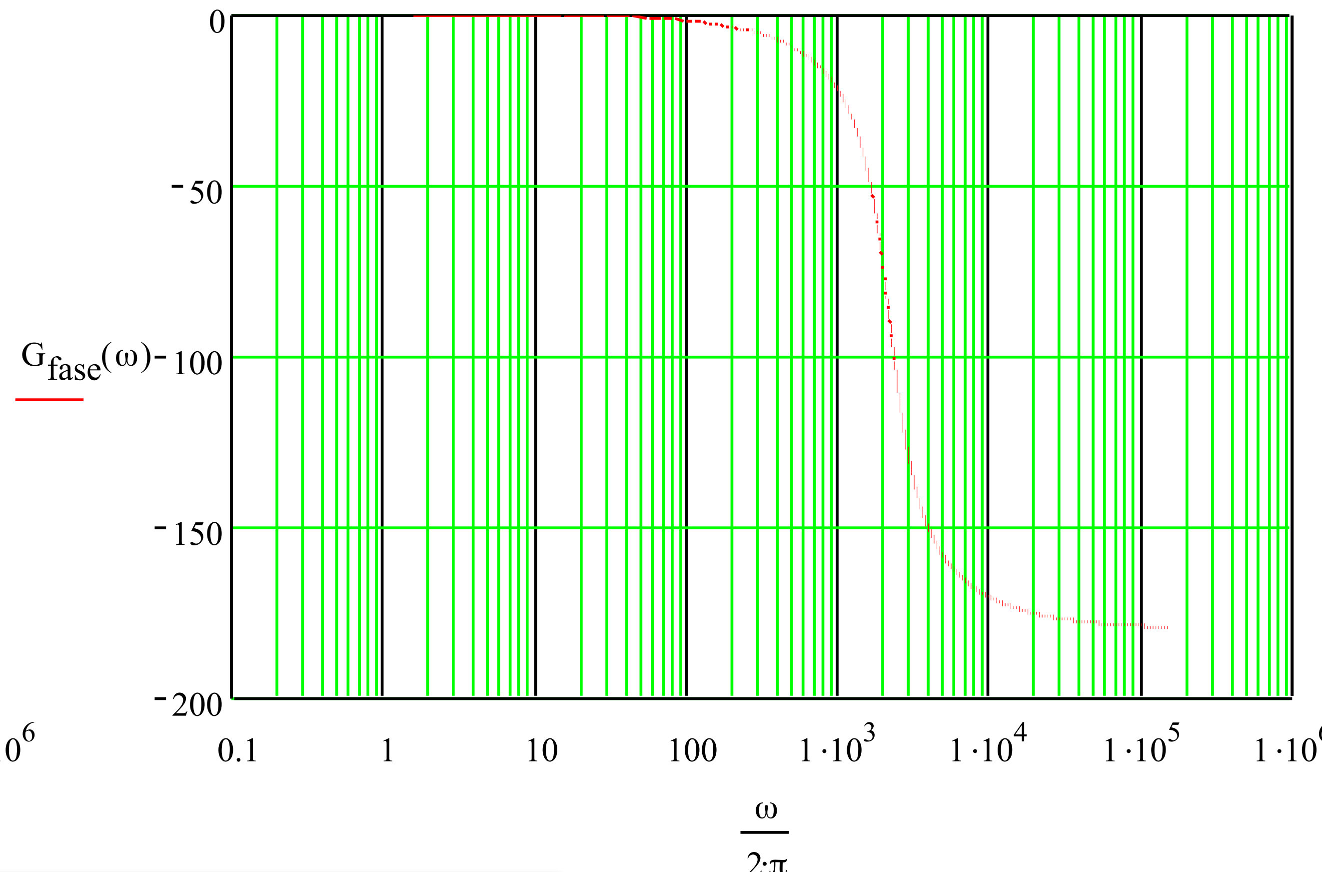
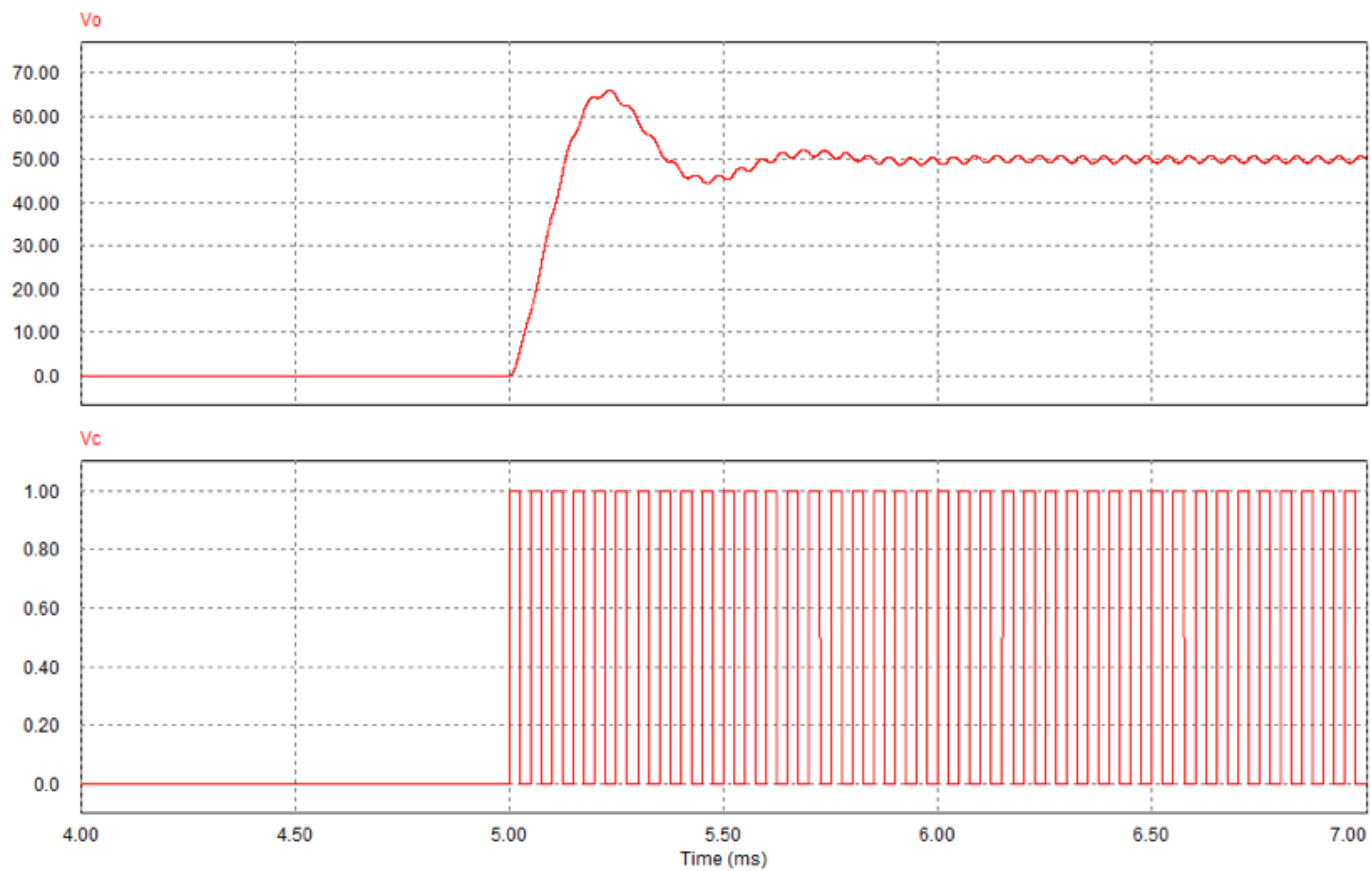




Diagrama de bode de módulo e fase.

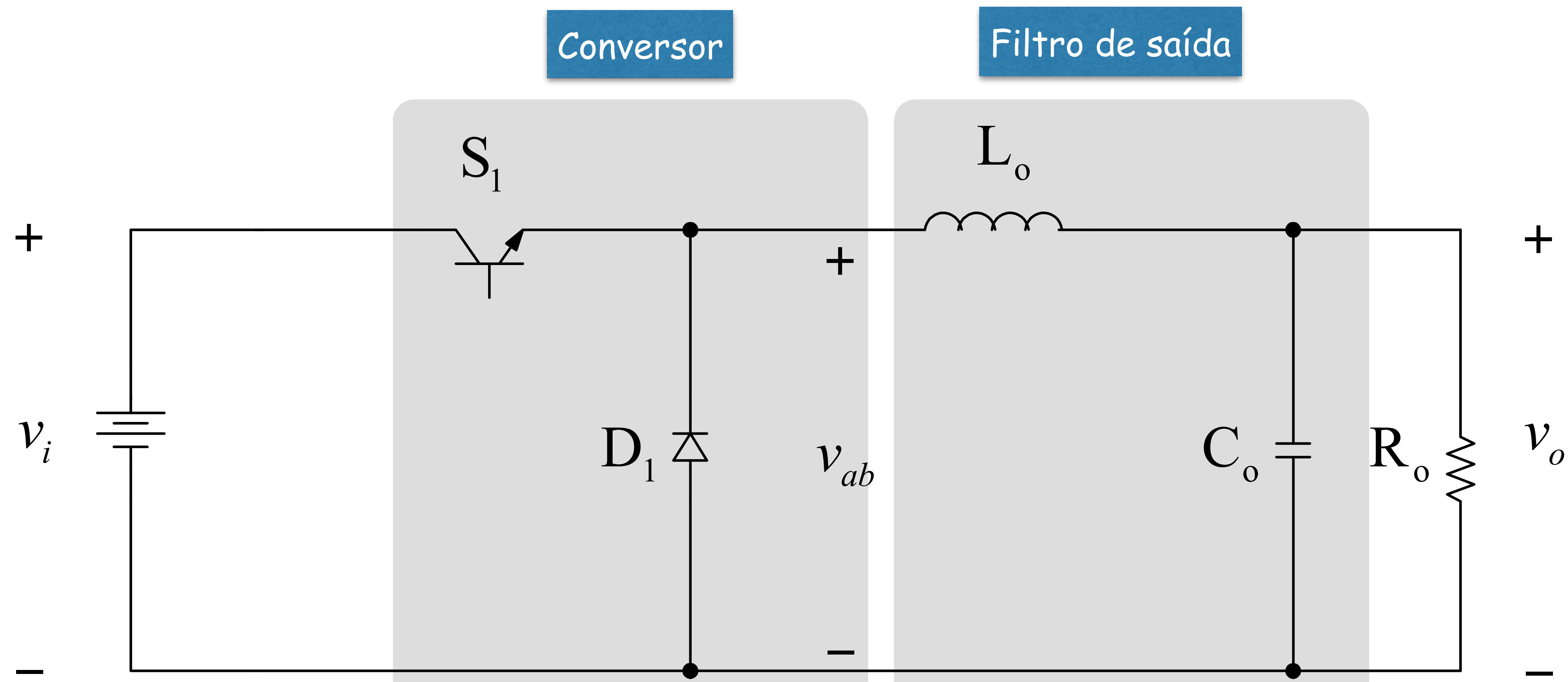
# Função de Transferência dos Conversores

## Função de transferência da tensão de saída pela razão cíclica G(s):



# Função de Transferência dos Conversores

## Função de transferência da tensão de saída pela tensão de entrada F(s):

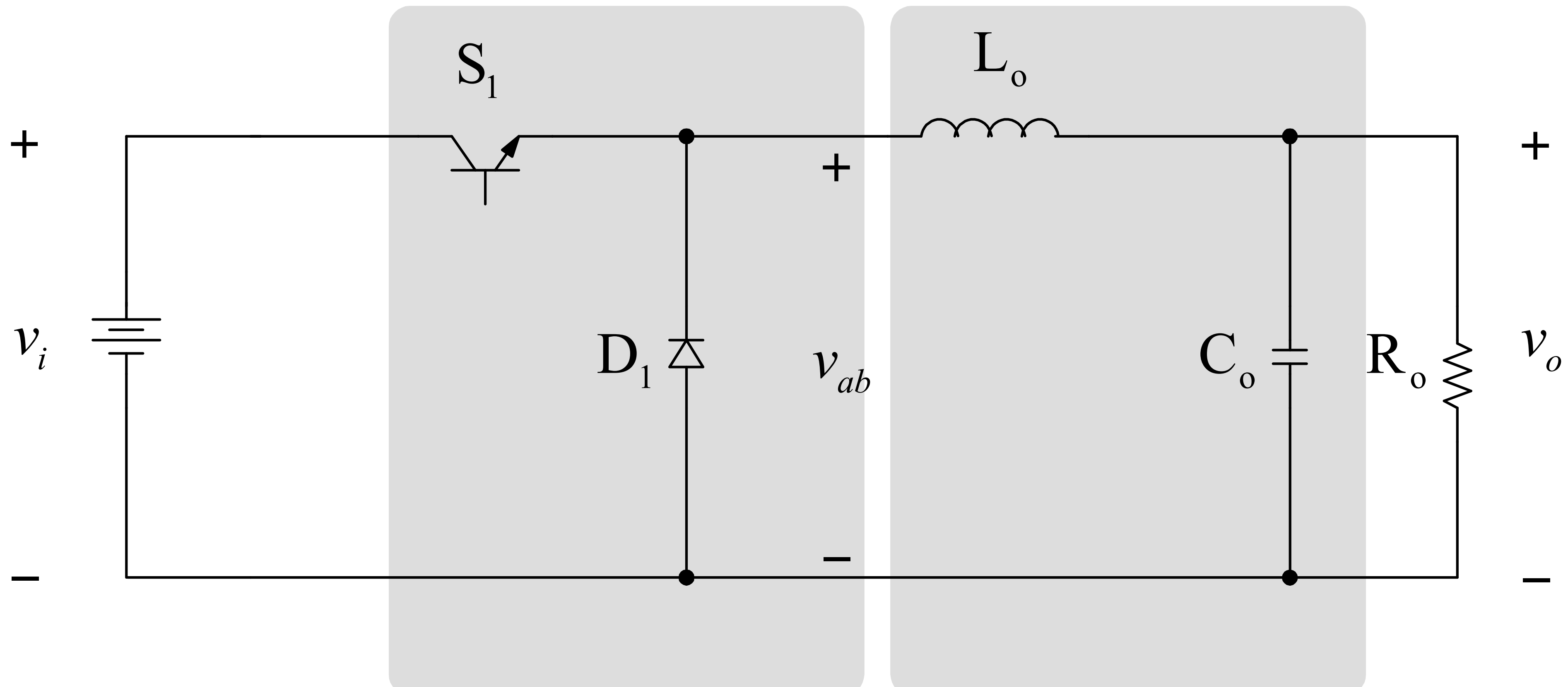



$$F_1(s) = \frac{\hat{V}_{ab}}{\hat{V}_i}$$

$$F_2(s) = \frac{\hat{V}_o}{\hat{V}_{ab}}$$

# Função de Transferência dos Conversores

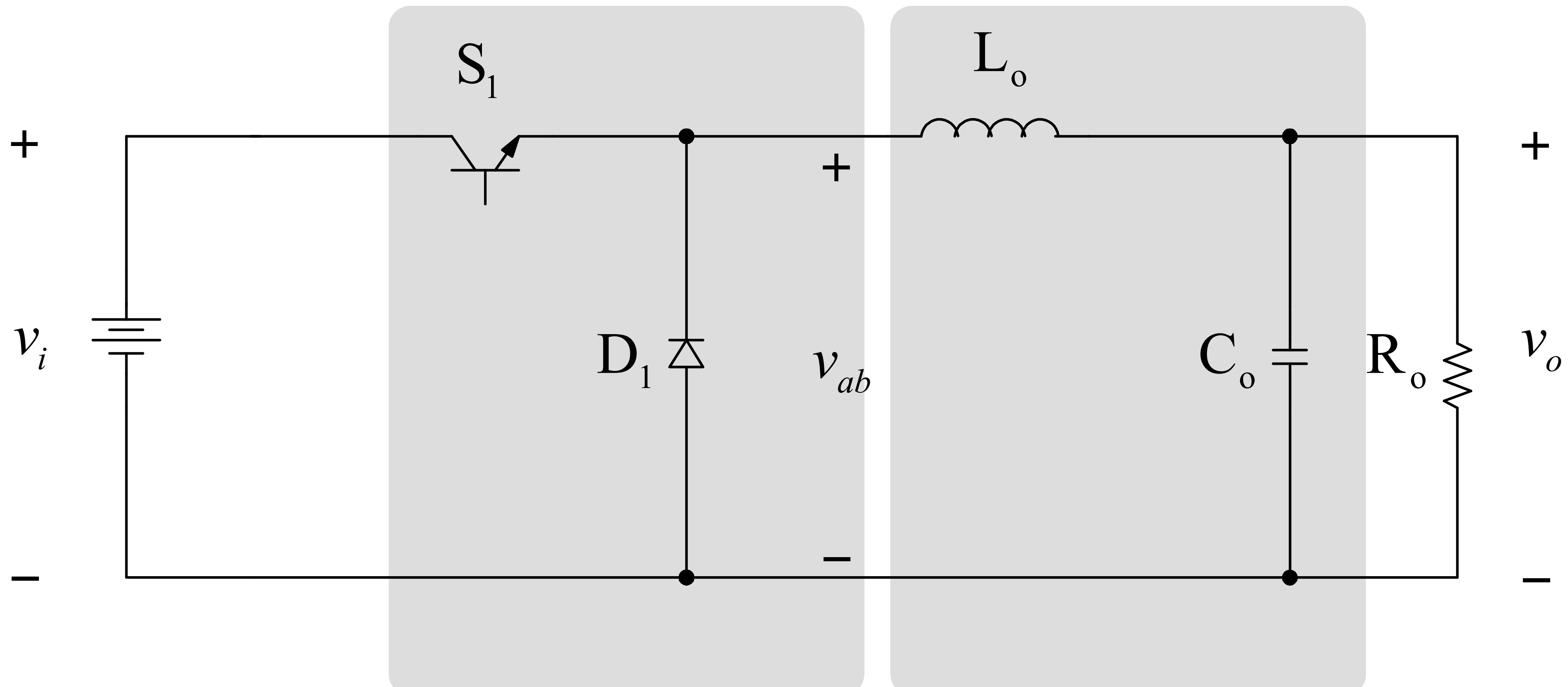
## Função de transferência da tensão de saída pela tensão de entrada F(s):




$$F(s) = F_1(s) \cdot F_2(s) = \frac{\hat{v}_{ab}}{\hat{v}_i} \cdot \frac{\hat{v}_o}{\hat{v}_{ab}} = \frac{\hat{v}_o}{\hat{v}_i} = D \cdot \frac{R_o}{s^2 \cdot L_o \cdot C_o \cdot R_o + s \cdot L_o + R_o}$$

# Função de Transferência dos Conversores

## Função de transferência da tensão de saída pela tensão de entrada F(s):

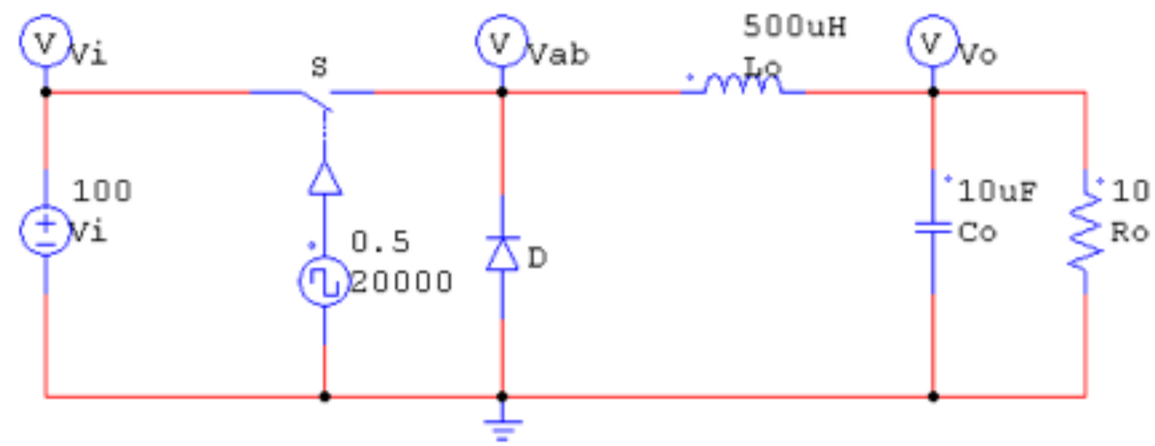


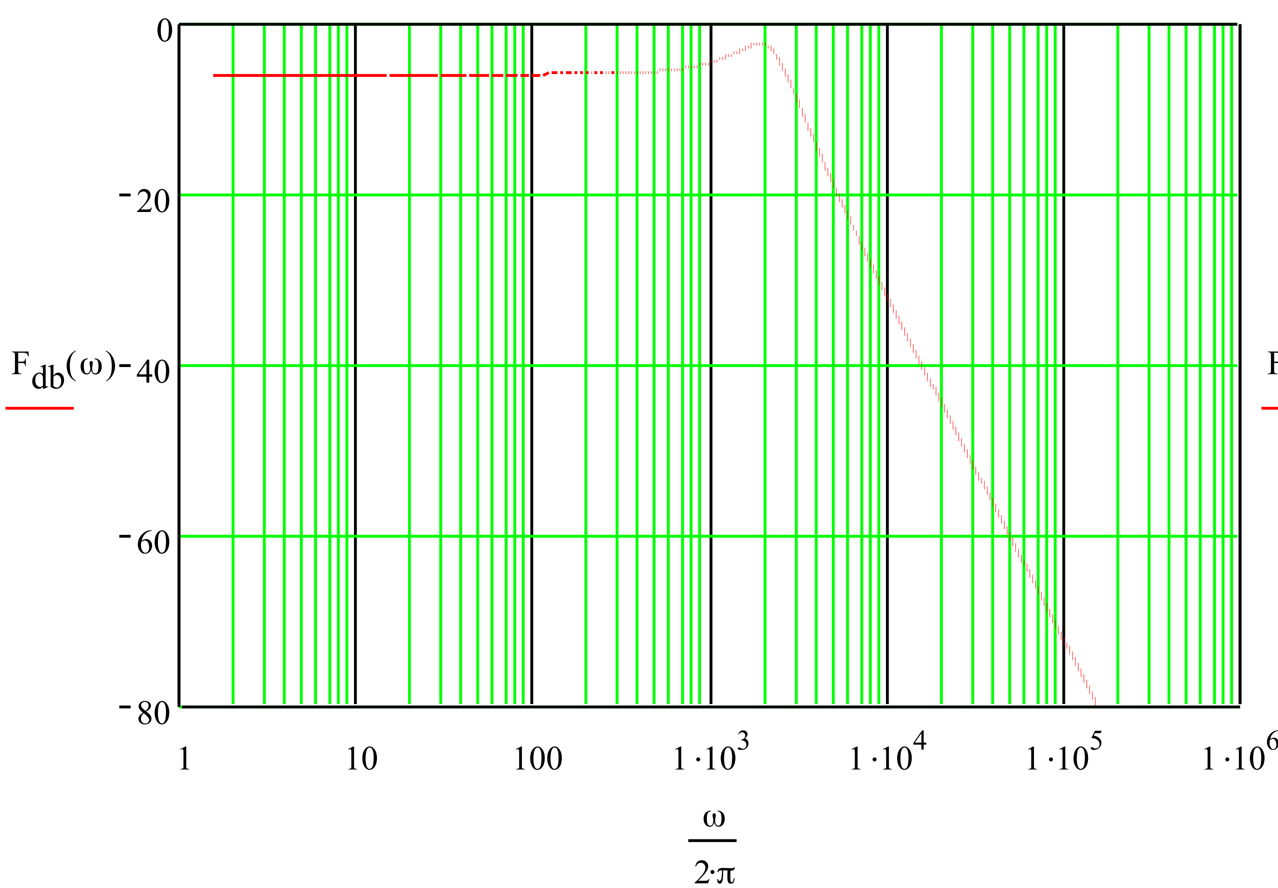

$$F(s) = \frac{D \cdot R_o}{s^2 \cdot L_o \cdot C_o \cdot R_o + s \cdot L_o + R_o}$$

# Função de Transferência dos Conversores

Função de transferência da tensão de saída pela tensão de entrada F(s):

$$F(s) = \frac{D \cdot R_o}{s^2 \cdot L_o \cdot C_o \cdot R_o + s \cdot L_o + R_o}$$



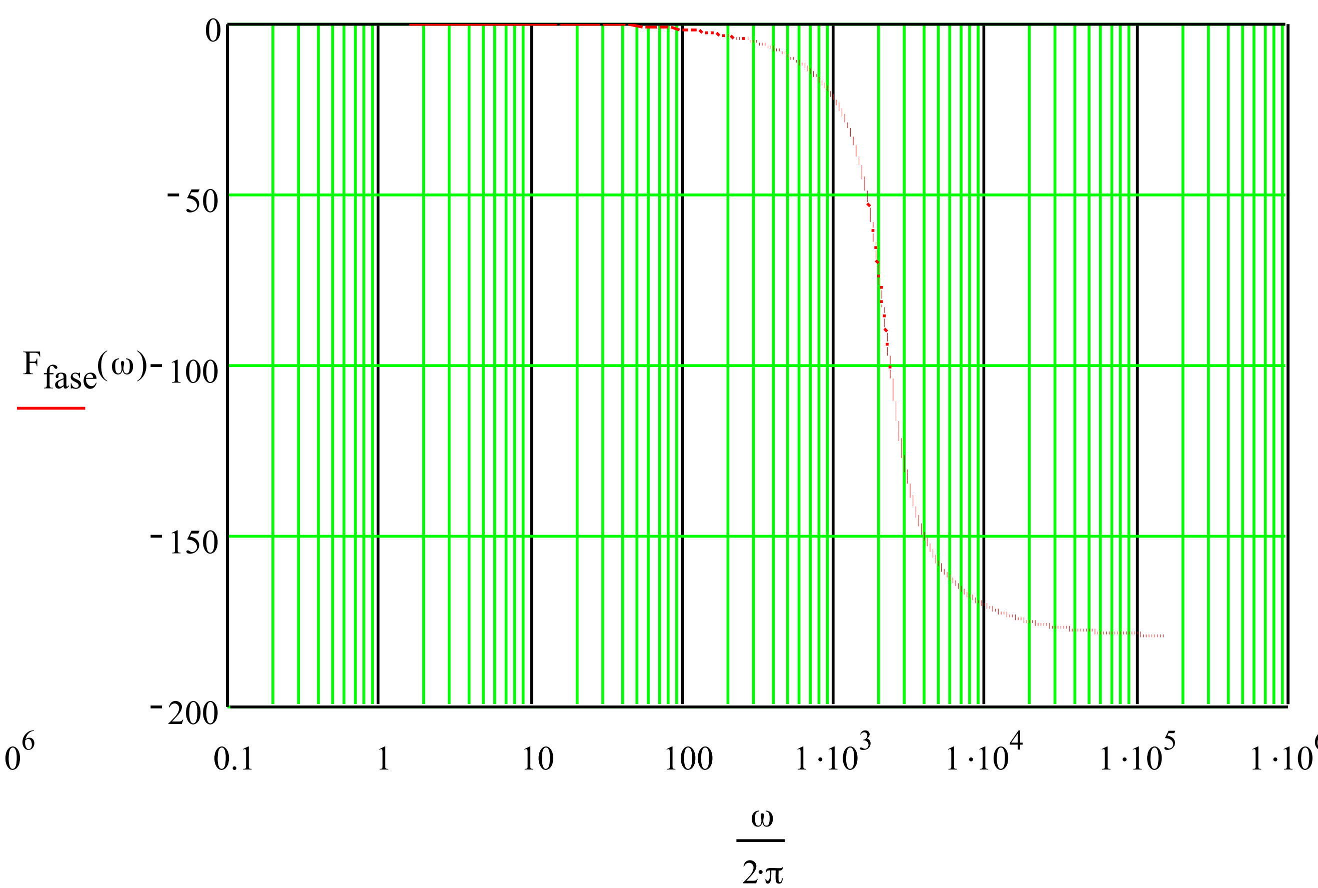
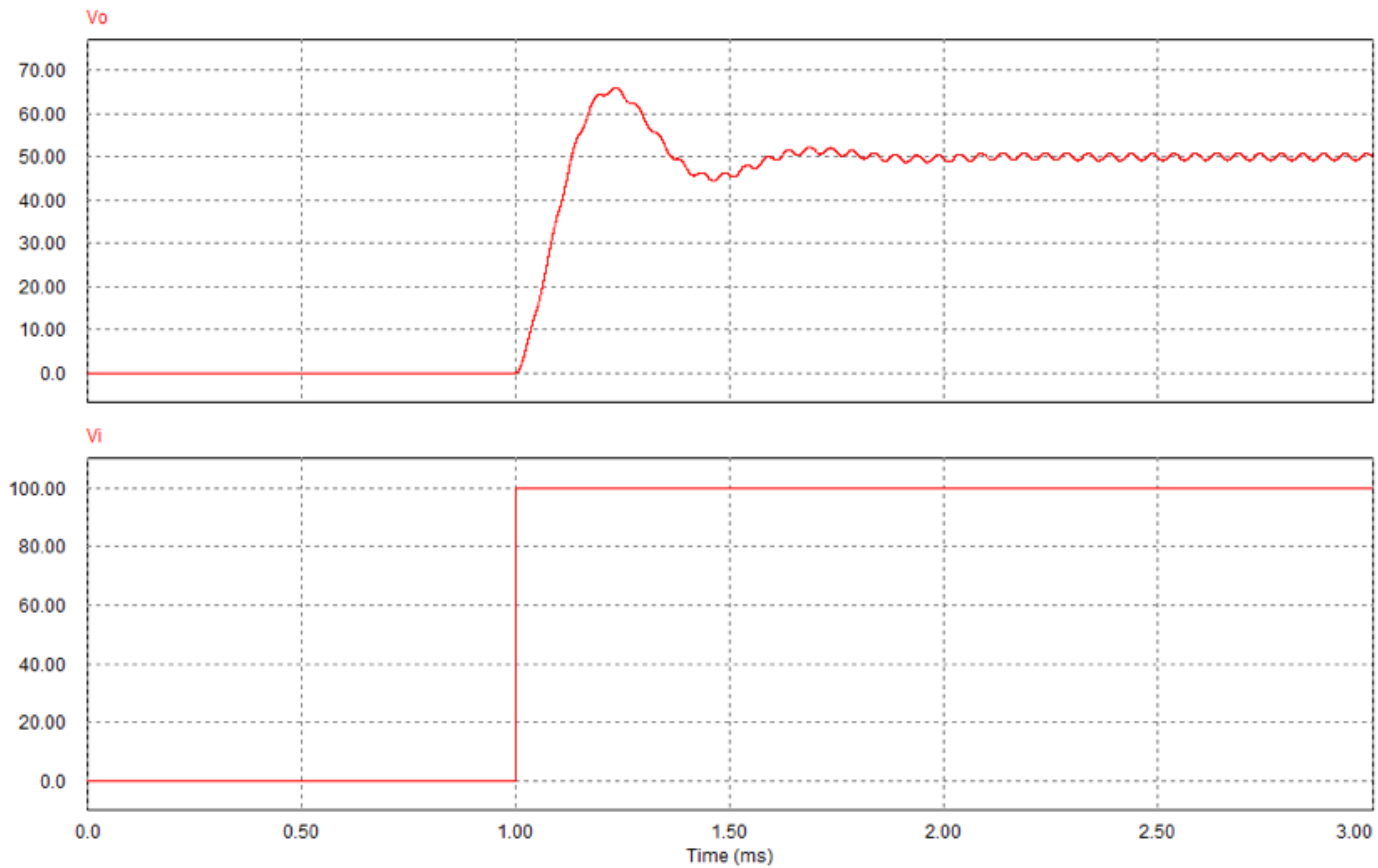




Diagrama de bode de módulo e fase.

# Função de Transferência dos Conversores

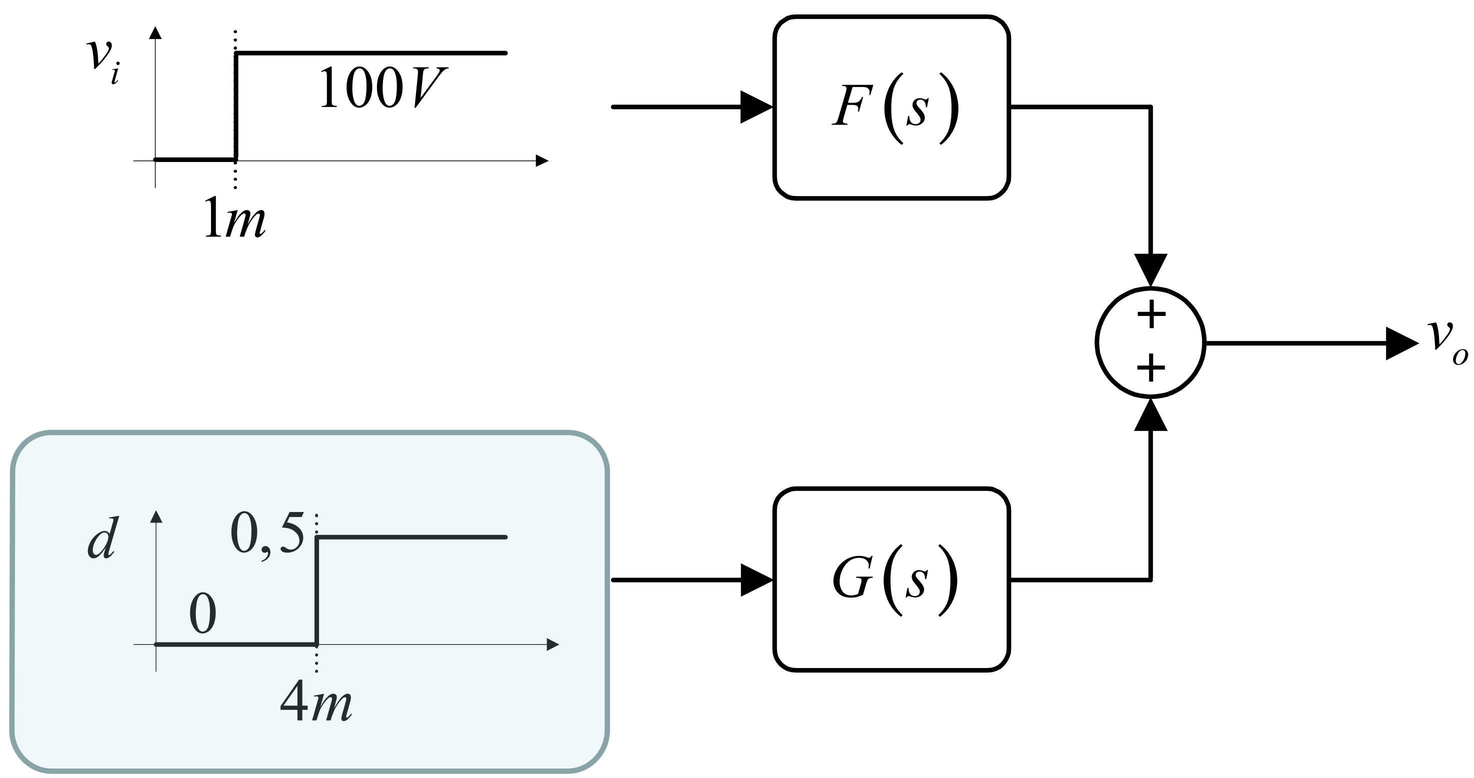
## Função de transferência da tensão de saída pela tensão de entrada F(s):



# Função de Transferência dos Conversores

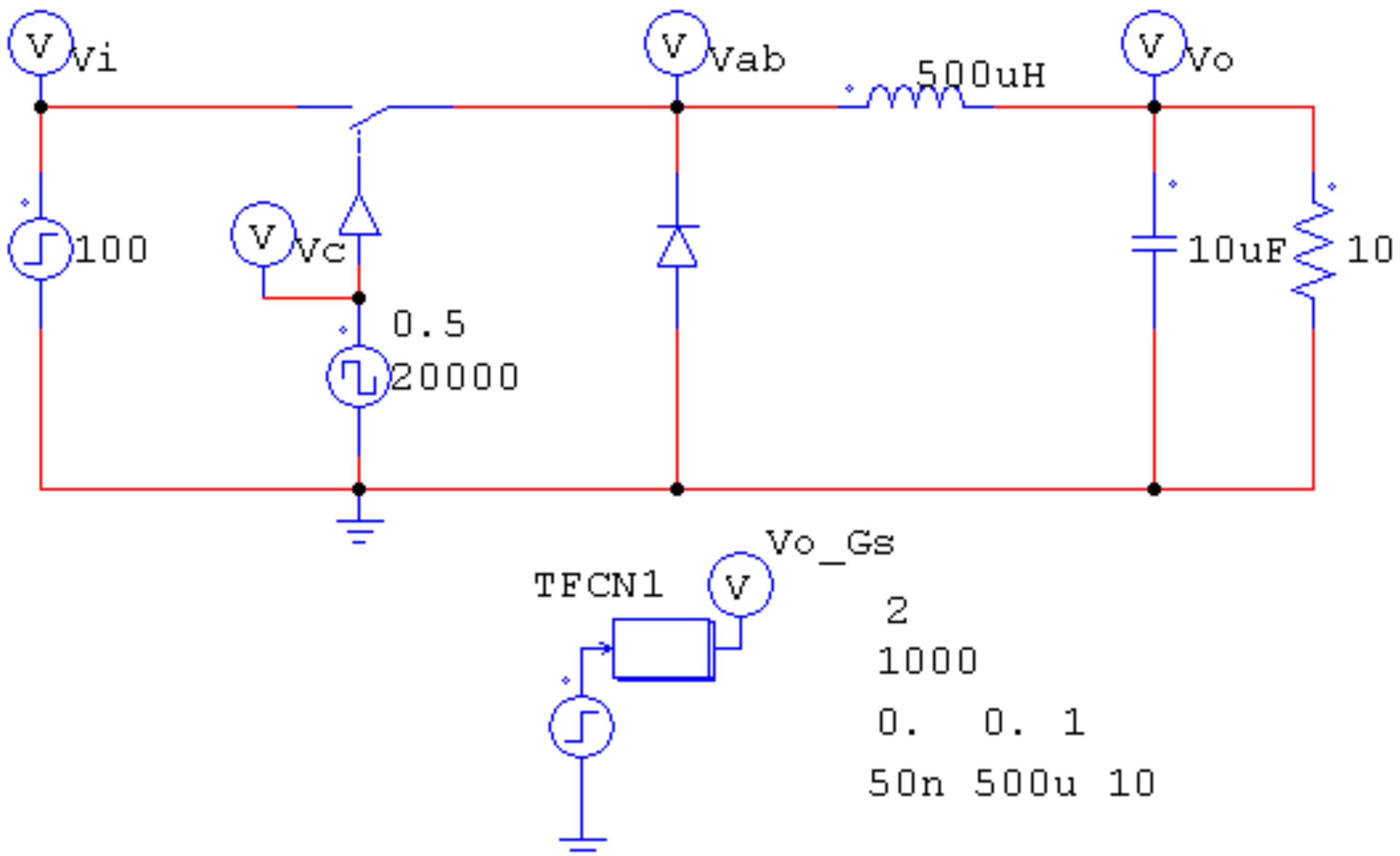
## Função de transferência da tensão de saída pela razão cíclica G(s):

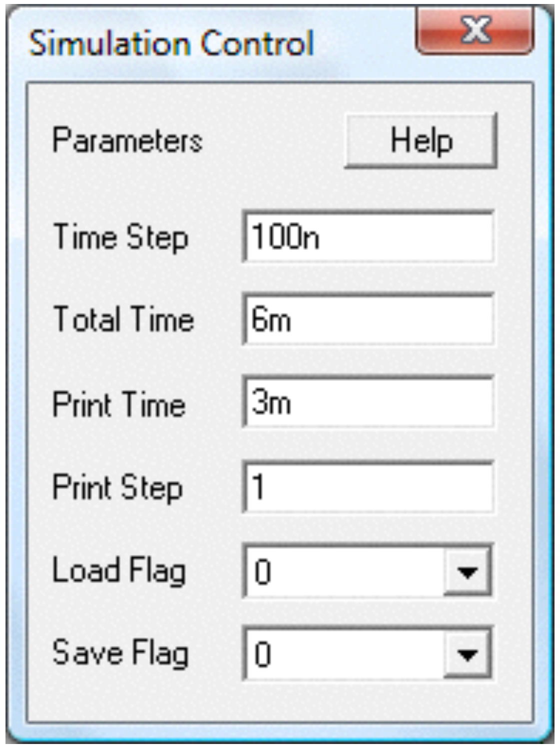
$$G(s) = \frac{V_i \cdot R_o}{s^2 \cdot L_o \cdot C_o \cdot R_o + s \cdot L_o + R_o} = \frac{1000}{s^2 \cdot 50 \cdot 10^{-9} + s \cdot 500 \cdot 10^{-6} + 10}$$



# Função de Transferência dos Conversores

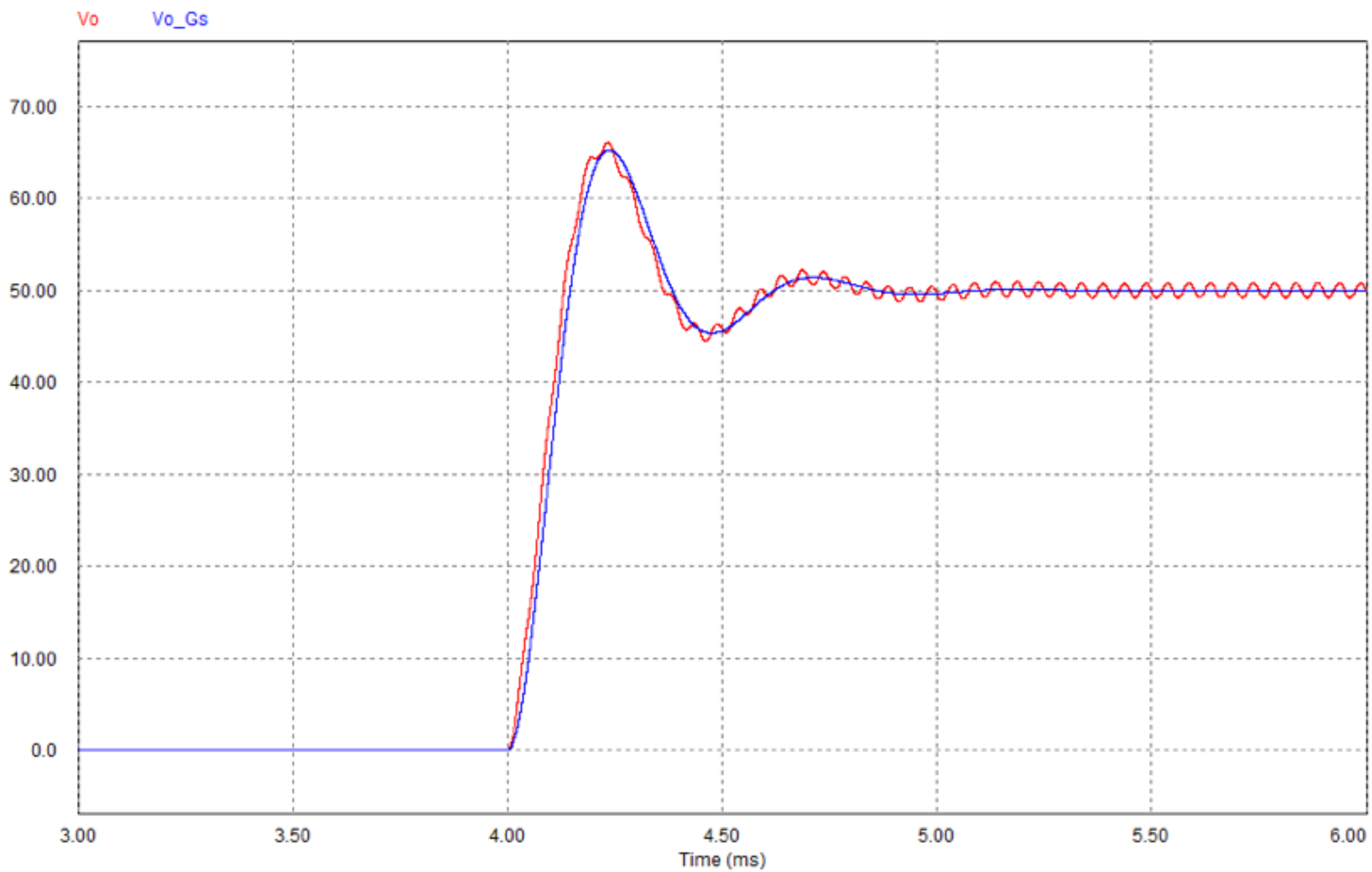
## Função de transferência da tensão de saída pela razão cíclica G(s):



# Função de Transferência dos Conversores

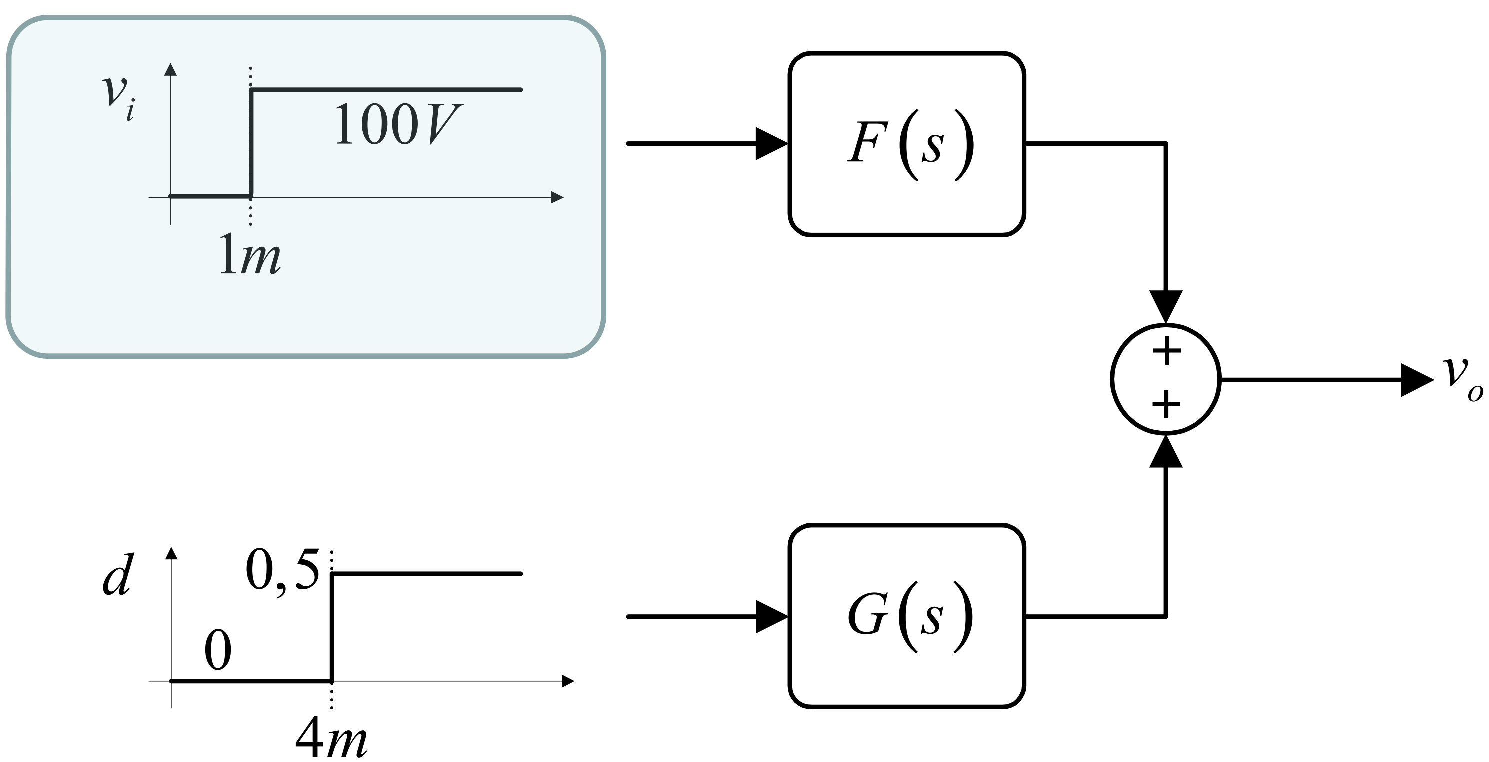
## Função de transferência da tensão de saída pela razão cíclica G(s):



# Função de Transferência dos Conversores

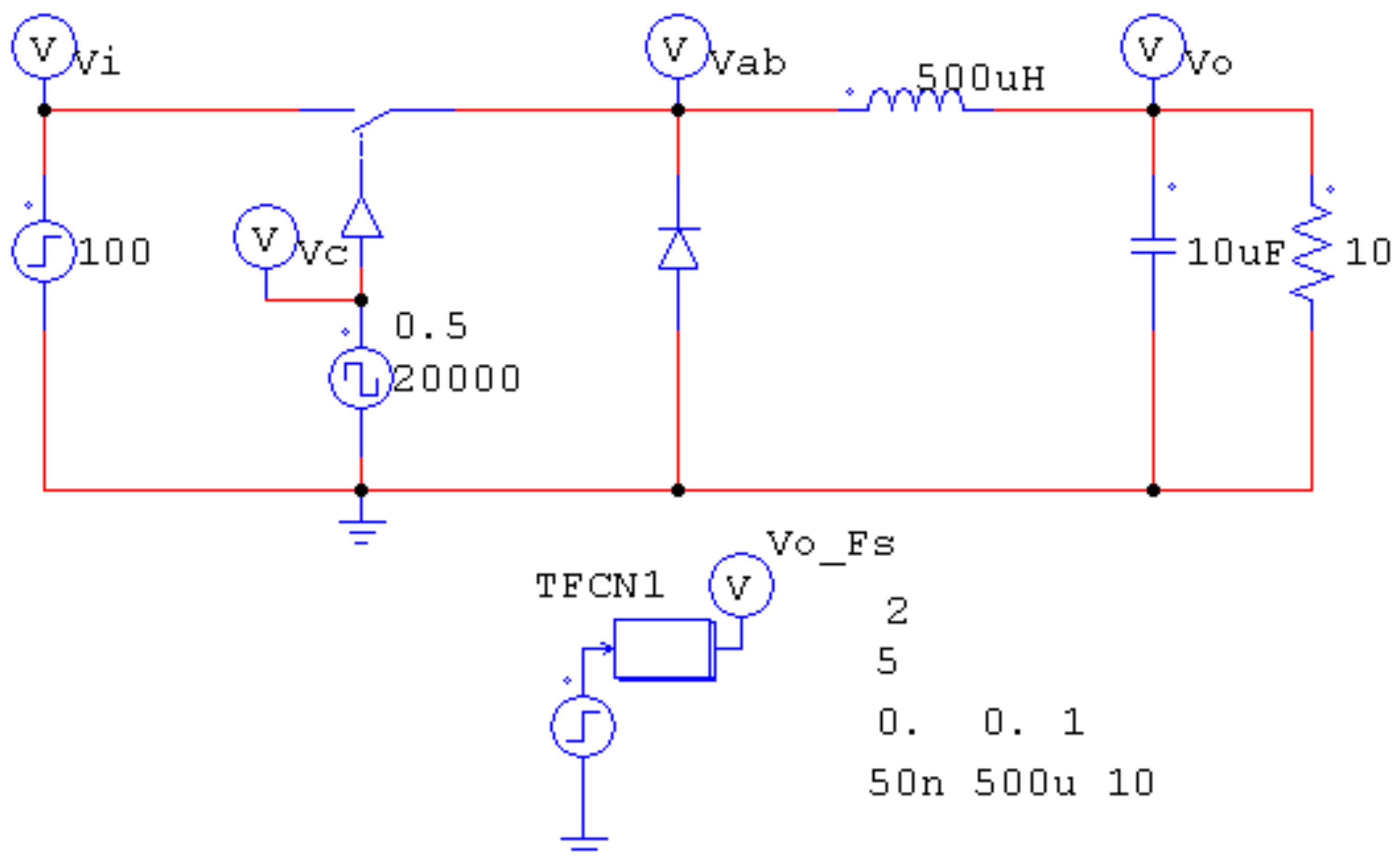
## Função de transferência da tensão de saída pela tensão de entrada F(s):

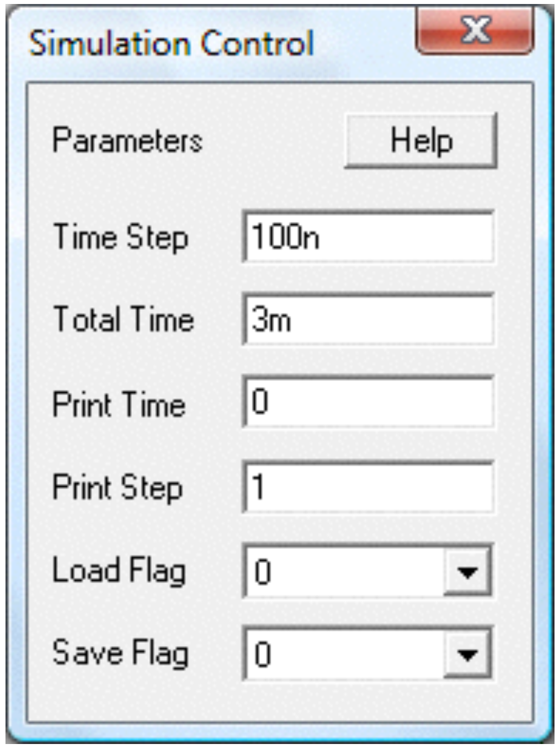
$$F(s) = \frac{D \cdot R_o}{s^2 \cdot L_o \cdot C_o \cdot R_o + s \cdot L_o + R_o} = \frac{5}{s^2 \cdot 50 \cdot 10^{-9} + s \cdot 500 \cdot 10^{-6} + 10}$$



# Função de Transferência dos Conversores

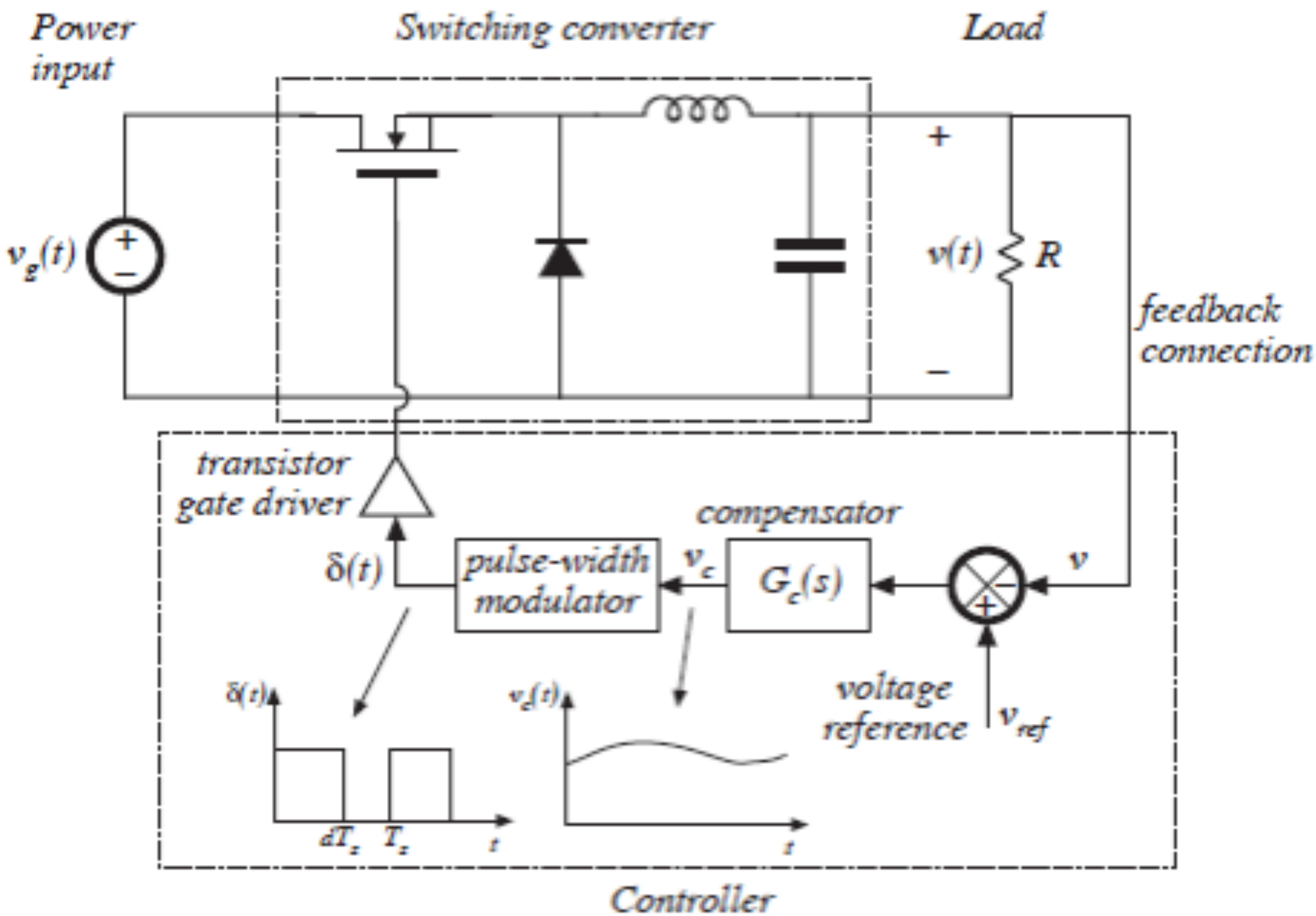
## Função de transferência da tensão de saída pela tensão de entrada F(s):



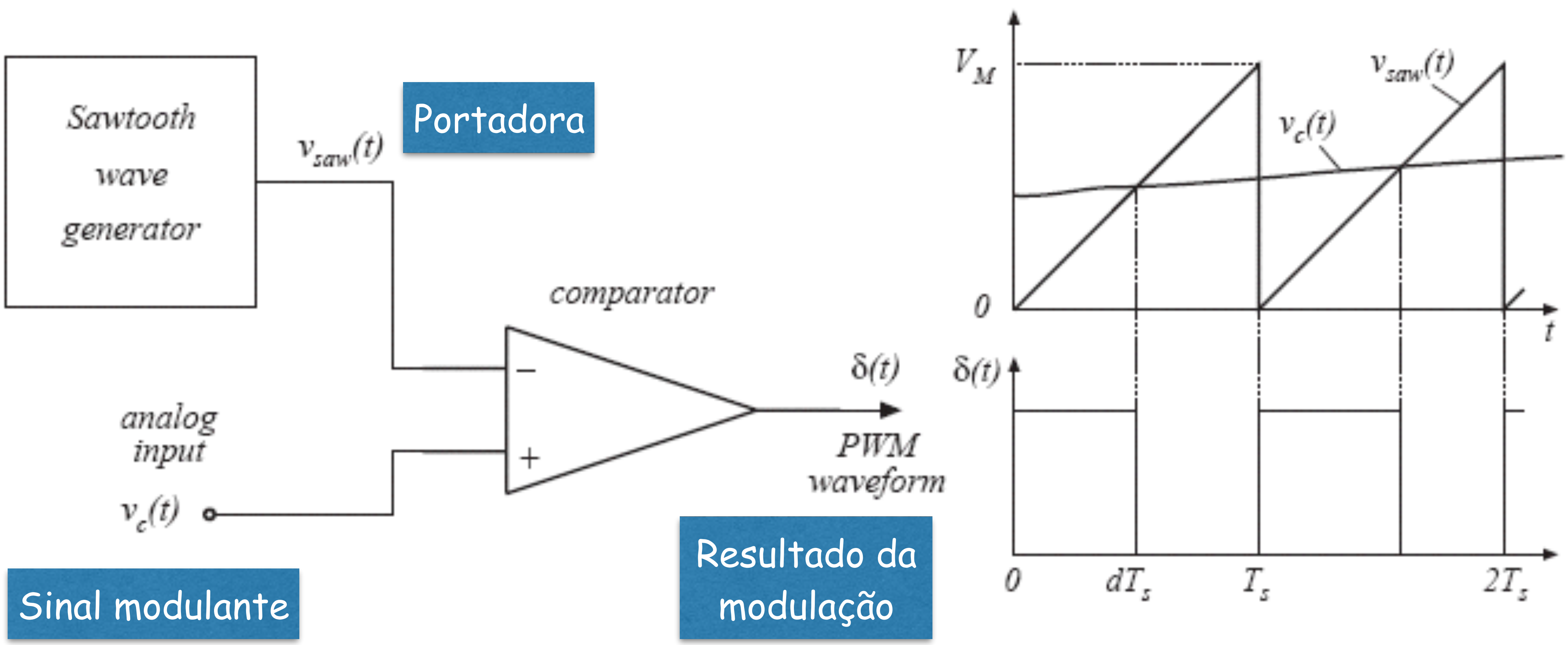



# Função de Transferência do Estágio de Modulação

**Conversor Buck**



# Função de Transferência do Estágio de Modulação




**Considerações:**

- A portadora define a freqüência de comutação;
- O sinal modulante deve ser aproximadamente contínuo durante um período da portadora;
- O sinal modulante define a fundamental da grandeza de saída do conversor.

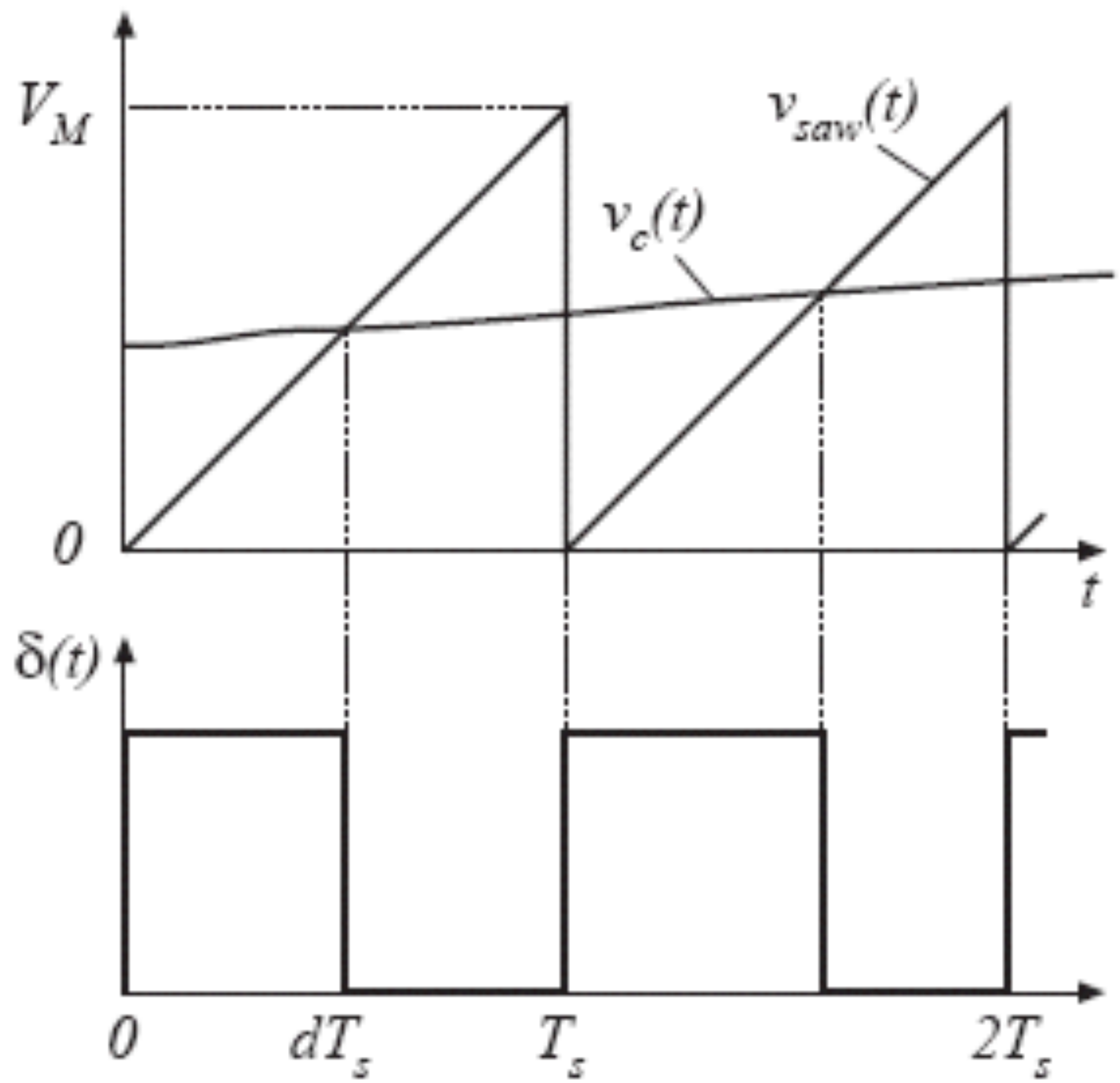
# Função de Transferência do Estágio de Modulação

Considerando uma dente-de-serra linear:

$$d(t) = \frac{v_c(t)}{V_M}$$

Para:

$$0 \le v_c(t) \le V_M$$



# Função de Transferência do Estágio de Modulação

**Perturbando o sinal no tempo:**

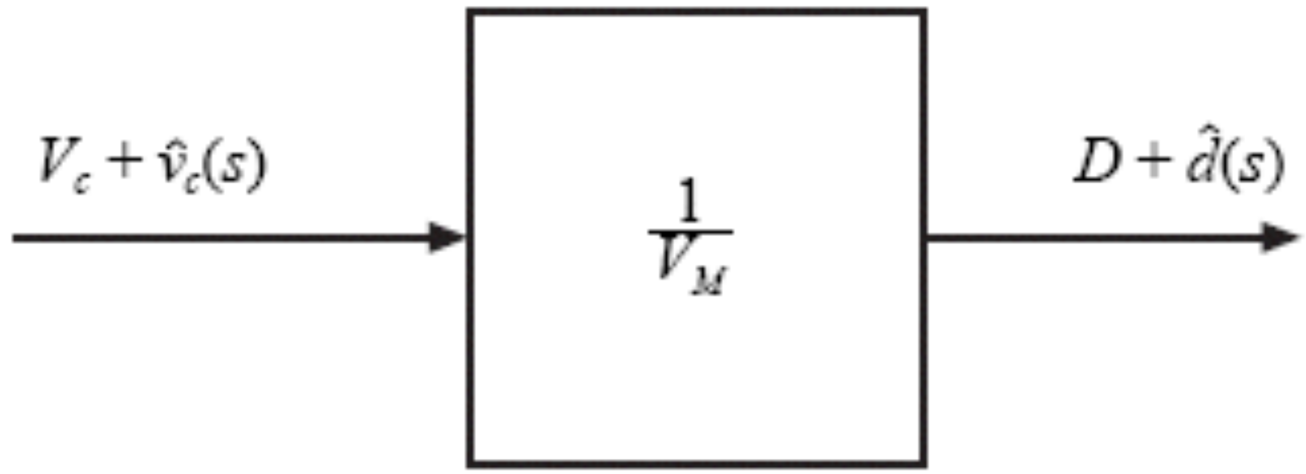
$$d(t) = D + \hat{d}(t)$$

$$v_c(t) = V_c + \hat{v}_c(t)$$

Resultado:

$$d(t) = \frac{v_c(t)}{V_M}$$

$$D + \hat{d}(t) = \frac{V_c + \hat{v}_c(t)}{V_M}$$




*pulse-width modulator*

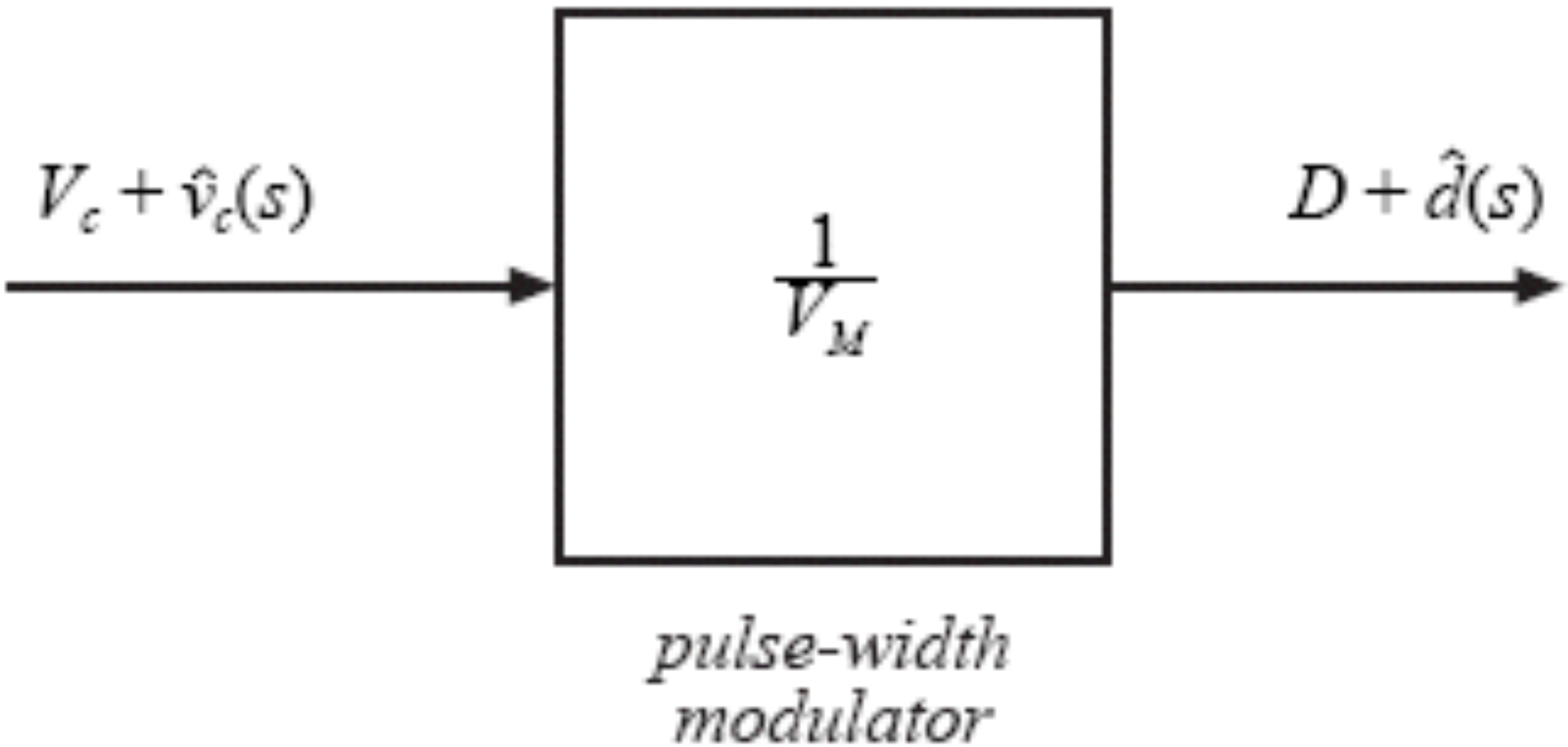
Relações CC:

$$\boxed{D = \frac{V_c}{V_M}}$$

Relações CA:

$$\boxed{\hat{d}(t) = \frac{\hat{v}_c(t)}{V_M}}$$

# Função de Transferência do Estágio de Modulação




$$D = \frac{V_c}{V_M}$$

CC

$$\hat{d}(t) = \frac{\hat{v}_C(t)}{V_M}$$

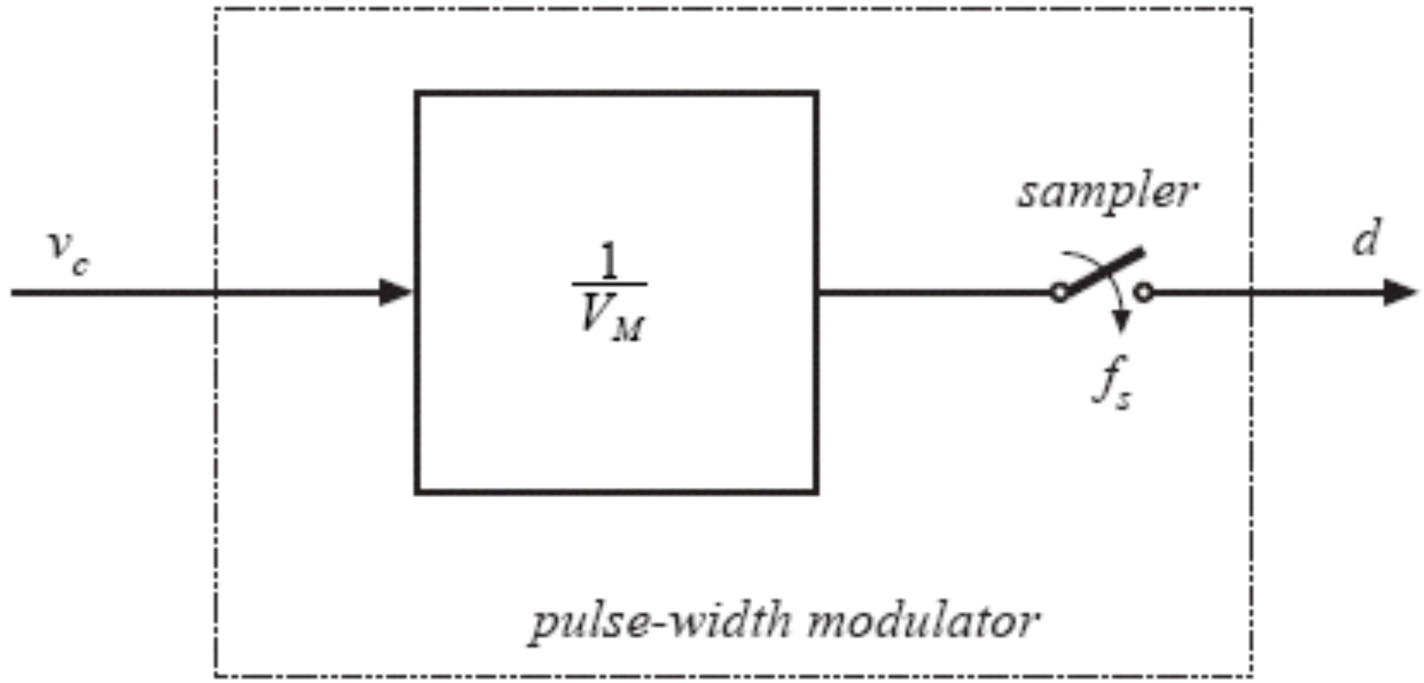
No tempo

$$D(s) = \frac{V_c(s)}{V_M}$$

Na freqüência

# Função de Transferência do Estágio de Modulação

**Amostragem do sinal modulante (tensão de controle):**




**Considerações:**

- Ocorre uma amostragem da tensão de controle a cada período de comutação;
- Assim, o teorema da amostragem (Nyquist) deve ser levado em conta:

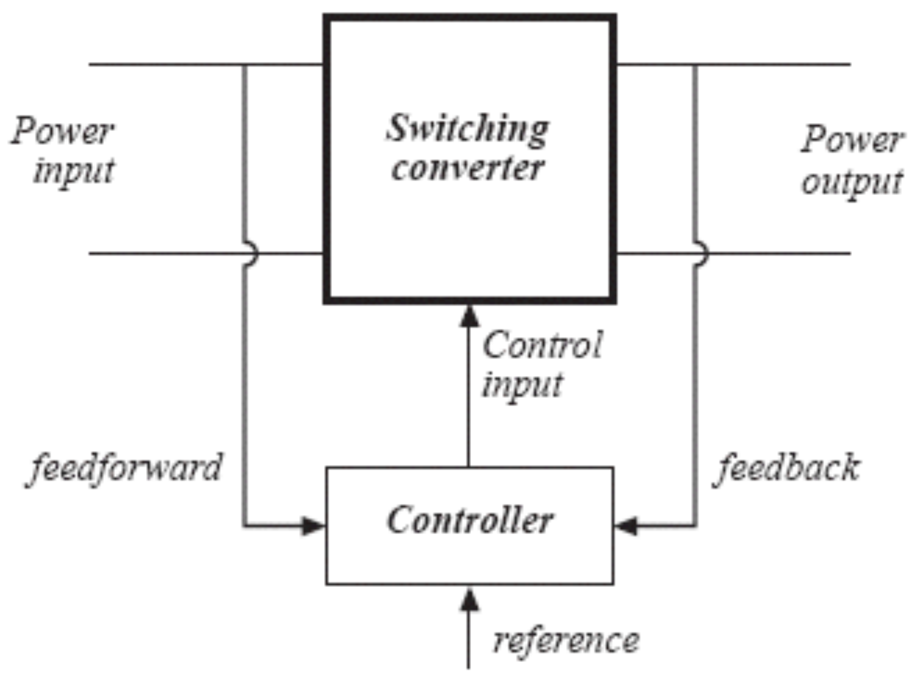
$$<< \frac{F_s}{2}$$

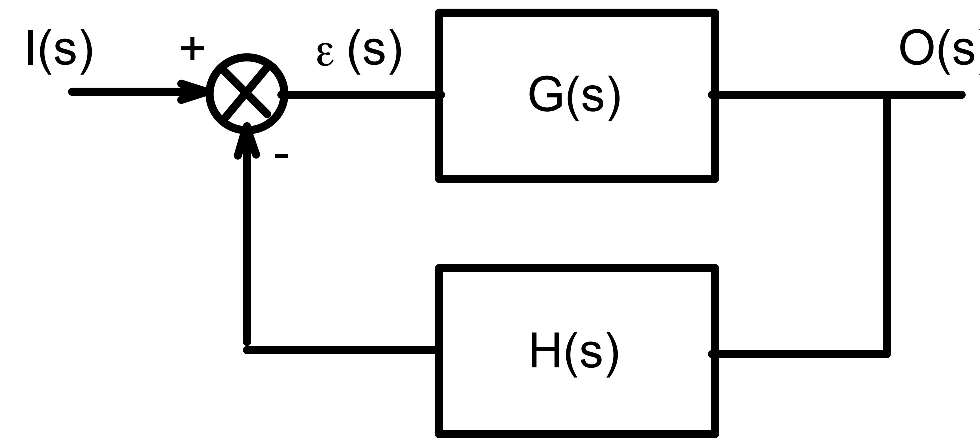
# Próxima Aula

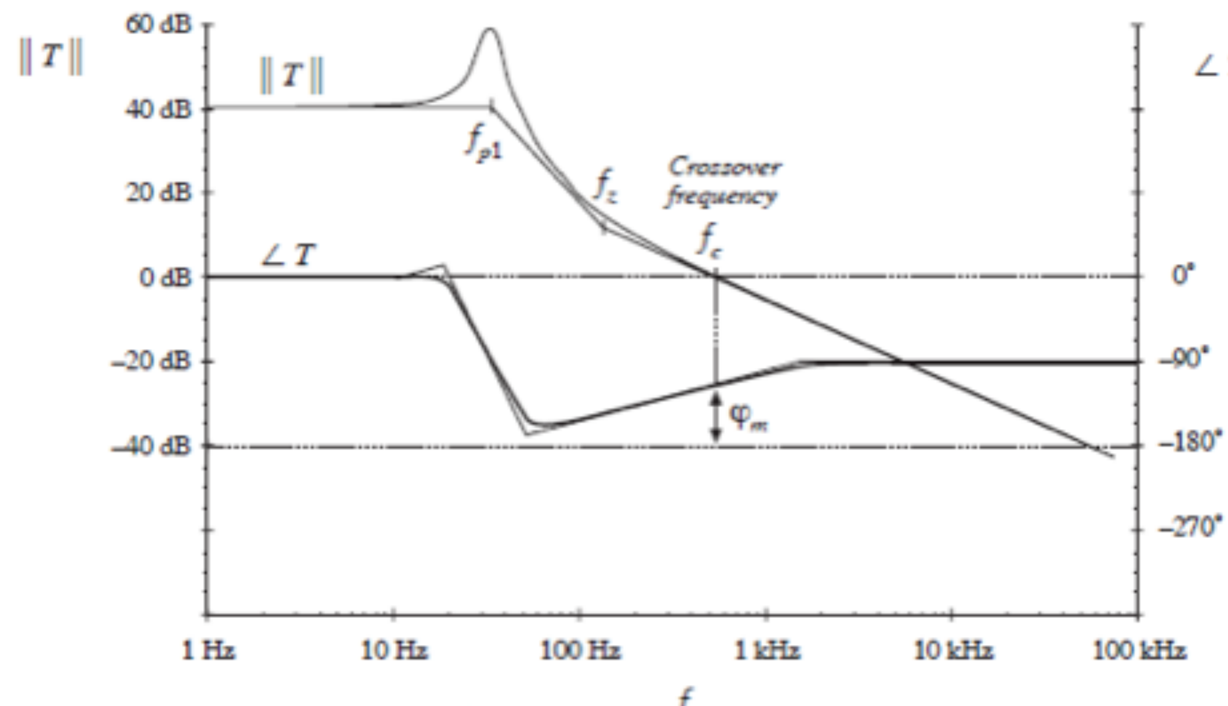
**Controle de conversores cc-cc:**

- Modelagem dos conversores;
- Controle de conversores.

Continua...




$\angle T(j2\pi f_c) = -112^\circ$

$\varphi_m = 180^\circ - 112^\circ = +68^\circ$